DOE/NE-ID-11188
December 2004

U.S. Department of Energy
Idaho Operations Office

Idaho National Engineering and Environmental Laboratory Operable Unit 10-08 Sitewide Groundwater Model Work Plan

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DOE/NE-ID-11188
Revision 0
Project No. 23368

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December 2004

Prepared for the
U.S. Department of Energy
DOE Idaho Operations Office

ABSTRACT

This work plan presents the strategy for preparing updated conceptual and numerical groundwater models for Waste Area Group 10, Operable Unit 10-08, at the Idaho National Engineering and Environmental Laboratory (INEEL). These models will support a comprehensive evaluation and cumulative risk analysis of environmental impacts from INEEL operations to the underlying Snake River Plain Aquifer for the Operable Unit 10-08 remedial investigation and feasibility study. Additionally, the model will serve to integrate knowledge gained during investigations of individual waste area groups into a comprehensive aquifer management tool for long-term stewardship responsibilities. This plan outlines the work elements associated with modeling efforts. These efforts will consist of the revision and documentation of the subregional conceptual model of groundwater flow at the INEEL based on current knowledge, identification of data gaps and the recommended approach for filling those gaps, preparation of an Operable Unit 10-08 numerical model of subregional groundwater flow based on the updated conceptual model, and development of a numerical model of contaminant transport to support a comprehensive INEEL groundwater risk assessment.

CONTENTS

FIGURES

TABLES

ACRONYMS

ANL-W	Argonne National Laboratory-West
AVH	axial volcanic high
BLT	Big Lost Trough
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFA	Central Facilities Area
cfs	cubic feet per second
CV	coefficient of variation
DCE	dichloroethene
DOE	U.S. Department of Energy
EIS	environmental impact statement
EPA	Environmental Protection Agency
ESRP	Eastern Snake River Plain
GMS	Groundwater Modeling System
INEEL	Idaho National Engineering and Environmental Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
IWRRI	Idaho Water Resources Research Institute
MCL	maximum contaminant level
MNA	monitored natural attenuation
NPTF	New Pump and Treat Facility
OU	operable unit
PCE	tetrachloroethene
PEST	Parameter Estimation
RI/FS	remedial investigation/feasibility study
ROD	record of decision
RWMC	Radioactive Waste Management Complex

SDA	Subsurface Disposal Area
SRPA	Snake River Plain Aquifer
SWGM	sitewide groundwater model
TAN	Test Area North
TCE	trichloroethene
TRA	Test Reactor Area
TSF	Technical Support Facility
UC	University of California
USGS	United States Geological Survey
VOC	volatile organic compound
WAG	waste area group

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1. INTRODUCTION

The purpose of Waste Area Group (WAG) 10, Operable Unit (OU) 10-08, groundwater modeling studies is to provide a comprehensive evaluation of environmental impacts from operations at the Idaho National Engineering and Environmental Laboratory (INEEL) to the underlying Snake River Plain Aquifer (SRPA). In particular, OU 10-08 groundwater studies address areas outside the boundaries of the other individual INEEL WAGs and consider the potential for risk created by commingling of residual plumes left by those WAGs. The cumulative impacts on the SRPA will be evaluated during the OU 10-08 remedial investigation/feasibility study (RI/FS).

A key component of the RI/FS effort (DOE-ID 2002a) and long-term stewardship of the groundwater resources at the INEEL is the development of an INEEL sitewide groundwater-flow and contaminant-transport numerical model. The model will support decisions and serve as a tool for managing, compiling, and synthesizing data regarding the SRPA beneath the INEEL. Currently, several different aquifer models are used at the INEEL to satisfy specific program needs. These models are not consistent in some cases and are sometimes redundant in the regimes they represent. Preparation of the OU 10-08 sitewide groundwater model (SWGM) provides the opportunity to promote consistency and eliminate redundancies in INEEL aquifer models. In the short term, the SWGM will be used to satisfy requirements for preparation of the OU 10-08 record of decision (ROD) and will supplement and support existing aquifer models. However, the design of the SWGM will eventually allow incorporation of smaller individual aquifer models in a seamless, consistent manner. Although vadose-zone transport modeling is the responsibility of individual WAGs, the assumptions and implementation used in the individual WAG vadose zone models will be reviewed as the contaminant fluxes are implemented into the SWGM.

The need for an OU 10-08 aquifer model is also driven by advancements in the understanding of the INEEL subsurface and greatly improved computational capabilities. During the past decade, INEEL contractors, the United States Geological Survey (USGS), and numerous academic institutions have obtained information that significantly changes the conceptual model of the subsurface beneath the Eastern Snake River Plain (ESRP). In order to use these new data in determining the risk posed by contaminants from the INEEL, the data must be compiled and used to update conceptual and numerical models of flow and transport. The purpose of this document is to present a plan to prepare updated conceptual and numerical models for OU 10-08.

1.1 Goals, Scope, and Products

The overall goal for the SWGM project is as follows, based on concurrence reached among U.S. Department of Energy (DOE) representatives, state and Environmental Protection Agency (EPA) regulators, and INEEL site contractors:

> *Develop a sitewide flow and transport model of the active flow portion of the Snake River Plain Aquifer that can be used to evaluate OU 10-08 remedial action alternatives and to ensure all remedies remain protective of the aquifer. The model will provide credible estimates of contaminant concentrations from sources at the INEEL over relevant future timeframes.*

In addition to achieving the overall project goal, the SWGM will likely be used by a variety of programs to meet several INEEL project objectives, including the following:

1. Assessment of long-term environmental impacts to the SRPA using predicted contaminant transport and dose modeling

2. Preparation of performance assessments and composite analyses required by DOE M 435.1-1, *Radioactive Waste Management Manual*

3. Evaluation of groundwater remediation strategies, including natural attenuation, hydraulic control/containment, and contaminant removal/cleanup

4. Synthesis and integration of subsurface knowledge into a single INEEL aquifer flow and transport model

5. Siting of new facilities

6. Evaluation of parameter uncertainty and the sensitivity of risk calculations to variations in modeling assumptions

7. Development of realistic alternative conceptual models that will help analysts in bounding the uncertainty in flow and transport simulation results

8. Management of groundwater resources

9. Communication of information regarding INEEL-scale fluid and contaminant movement to a wide range of audiences

10. Addressing questions from stakeholders and the public regarding groundwater contamination and transport at the INEEL.

The scope of the OU 10-08 SWGM is to evaluate the cumulative impact from individual INEEL contaminant sources on groundwater for potential receptors at any location within the boundary of the INEEL. As a consequence of this scope, the SWGM boundaries, hereafter referred to as the OU 10-08 model domain, must extend some distance beyond the INEEL boundary. The scale of investigation for the SWGM is defined as "subregional" for the purposes of this work plan and will be large enough to establish reasonable boundary conditions.

The primary products of the groundwater modeling will be as follows:

1. An updated conceptual model of flow in the SRPA, capturing the current understanding of the aquifer system in a form that can be used in a numerical simulator to predict groundwater flow and contaminant transport

2. A numerical modeling tool that can be used to predict the aquifer flow directions, water mass flux rates, and contaminant transport velocities and concentrations at the scale of the INEEL

3. A tool to ensure that remedies are protective of human health and the environment at the scale of the INEEL.

1.2 OU 10-08 Groundwater Modeling Strategy and Integration

To the extent possible, the SWGM will be structured to integrate with and complement existing groundwater flow and contaminant transport models developed by individual WAGs and the USGS. This approach will enhance consistency across the INEEL and help resolve differences raised by different interpretations of subsurface data. Communication, staff integration, and data sharing are the foremost components in the strategy for integrating the SWGM with existing models. Meetings will be held at regular intervals for technical and management staff involved with the active development or application of numerical simulations of the subsurface at the INEEL. Additionally, senior technical staff personnel have been recruited from the major facility-scale groundwater projects to act as technical consultants on the design and construction of the SWGM. Additionally, use of the Environmental Data Warehouse to share and store data will ensure that the SWGM is developed and based on a common and consistent set of data.

The underlying strategy for the SWGM is a departure from the strategies for other models that have sought a single, unique solution to groundwater flow and transport. The SWGM strategy assumes that different and sometimes competing interpretations of groundwater flow and transport will develop because of the relatively sparse subsurface data set for the complicated INEEL subsurface and the many programs utilizing these data for varied purposes. Consensus on a single conceptual model will be difficult to achieve and will evolve as more data become available. The SWGM strategy for integration includes the capability to test interpretations generated by various projects (solving specific problems). Cross comparison between interpretations will define the bounds of flow and transport in the aquifer at the scale of the INEEL. Thus, unique solutions derived by individual projects can be included in the SWGM as long as the solutions are consistent within a range that is reasonable for possible interpretations described by the subregional understanding of aquifer flow and transport.

1.3 Tasks Supporting the OU 10-08 RI/FS

Project personnel have identified the following tasks that must be completed in order to satisfy requirements for the groundwater aspects of the OU 10-08 RI/FS (tasks related to OU 10-08 soils will be developed separately):

1. Update and document the OU 10-08 subregional conceptual model of groundwater flow.
2. Identify data gaps, and make recommendations for filling them.
3. Prepare a new OU 10-08 numerical model of subregional groundwater flow based on the updated conceptual model. This modeling effort will consist of a set of two subregional groundwater flow models (i.e., two-dimensional for design and three-dimensional for implementation).
4. Coordinate with other WAG projects to provide a subregional numerical tool that is consistent with the intermediate-scale numerical models used for individual WAGs. To the extent practical, the OU 10-08 numerical model will integrate directly with the intermediate-scale models.
5. Develop a numerical model of contaminant transport for INEEL sitewide groundwater risk assessment. In particular, the objective is to identify areas where plumes might commingle, resulting in an unacceptable cumulative risk to groundwater users.

1.4 Long-term Tasks – Long-term Stewardship

SWGM project personnel have identified the following tasks that will support the transition from cleanup to long-term stewardship of the INEEL:

1. Assimilate and archive data and numerical models from individual WAGs that fall under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The objective of this task will be to provide a central location for comparing CERCLA-based modeling predictions to subsequent monitoring data during five-year reviews in order to ensure compliance with remedial action objectives and preserve numerical modeling capabilities over the long term.

2. Support management of groundwater quality at an INEEL sitewide scale to meet end-state objectives and long-term stewardship requirements through the development of integrated conceptual and numerical models, which will be used to assess groundwater sampling results, interpret data trends, and evaluate the protectiveness of selected remedies.

1.5 Background

Numerical modeling of groundwater flow beneath the INEEL has been ongoing for many years, both at the INEEL sitewide scale and for much larger areas of interest. Numerical models of INEEL groundwater were utilized as early as the mid-1970s (Robertson 1974). The USGS Regional Aquifer-System Analysis Program produced several models of the SRPA at various scales for use as characterization tools dealing with water-resource issues. CERCLA-mandated remedial investigations at the INEEL have resulted in several flow and transport models; these include three currently working numerical flow and transport models for individual WAGs.

1.5.1 Historical SRPA Groundwater Modeling

Historical modeling efforts are important, because they identify documented successes that can be incorporated into the SWGM and identify issues and problems that can be avoided. Several historical models provide input to the OU 10-08 conceptual model and provide useful summaries of data to be used in the SWGM. The following subsections summarize basic features and applicable results for several regional ESRP models, subregional INEEL models, and three active individual WAG aquifer models.

1.5.1.1 Numerical Modeling Studies from 1974 to 1990. In one of the first comprehensive subregional numerical transport-modeling studies, Robertson (1974) calibrated a two-dimensional flow and transport model with data from the early 1940s through 1972 and used the calibrated model to predict solute transport to the year 2000. Solutions were obtained using the method of characteristics. The model assumed a constant aquifer thickness of 250 ft and included both steady-state and transient-flow conditions. Minimum grid dimension was 4,183 ft on a variable grid oriented to the interpreted principal direction of regional groundwater flow. The grid consisted of 39 rows of cells along the principal axis of flow (southwest) and 36 columns of cells along the axis perpendicular to flow (southeast). Robertson's model domain represented an area of 2,548 mi^2 shown in Figure 1-1.

Robertson's transport model was used to predict groundwater concentrations of tritium, chloride, and strontium-90 emanating from the Test Reactor Area (TRA) and the Idaho Nuclear Technology and Engineering Center (INTEC). An important result of the work came from matching predicted chloride concentrations to observed chloride concentrations using an unexpectedly large ratio (1.5) of transverse (449 ft) to longitudinal dispersivity (298 ft). The model was first reworked by Lewis and Goldstein (1982) to evaluate this large ratio. Their analysis resulted in a list of problems with the original model, including, among other items, too coarse a grid for an accurate simulation of contaminant plumes. Goode and Konikow (1990) revisited the model a second time in an attempt to explain the transverse to longitudinal dispersivity ratio using transient recharge from the Big Lost River.

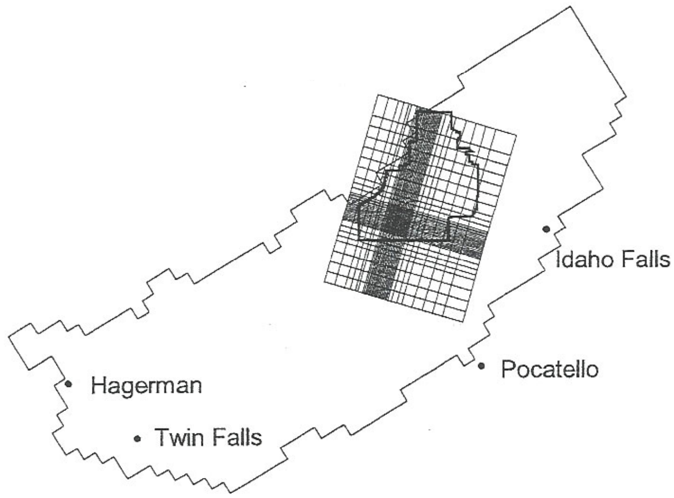


Figure 1-1. Domain and grid configuration of early flow and transport model (Robertson 1974) shown relative to major cities and the USGS ESRP model domain.

1.5.1.2 Spent Nuclear Fuel Environmental Impact Statement Model (1990). A two-dimensional, steady-state flow and transport model was developed (Arnett and Springer 1993) for the INEEL Spent Nuclear Fuel Program's environmental impact statement (EIS). The flow model simulated an area larger than the INEEL site to utilize natural boundary conditions. The model domain was similar to Robertson's model, as shown in Figure 1-2. The northern and southern boundaries were chosen far from the contaminant transport area of interest to minimize their effects on the solutions. These boundaries were modeled with constant heads interpolated from regional head maps. Recharge and discharge from INEEL ponds and wells were neglected.

This modeling effort assumed two-dimensional, horizontal flow and steady-state conditions in a heterogeneous, isotropic, confined aquifer. A structured, variable grid size was used with refinement in the transport areas of interest, which consisted of INTEC, the Naval Reactors Facility, the Radioactive Waste Management Complex (RWMC), Test Area North (TAN), and TRA. The grid axes were rotated counterclockwise from true north to match the regional flow direction. The model was developed using MAGNUM-3D, a finite-element code designed to model two- or three-dimensional transient or steady-state groundwater flow.

The transport model was constructed as a subarea of the flow model domain in the vicinity of INTEC, TRA, and RWMC and corresponding to the refined area of the flow model. The transport model simulated tritium, strontium-90, and iodine-129 plumes beneath TRA and INTEC. Transport was simulated using CHAINT, which is a two-dimensional, finite-element, solute-transport code. Tritium data from 1985 were used to calibrate transmissivity and effective porosity; strontium-90 and iodine-129 plume data were used to calibrate the strontium and iodine retardation.

However, this model could not satisfactorily simulate the observed plume configuration. The assumption of two-dimensional flow was considered reasonable for the regional-scale groundwater flow, but it was believed a transient flow simulation would be required to with this model better simulate the highly dispersed observed contaminant plumes.

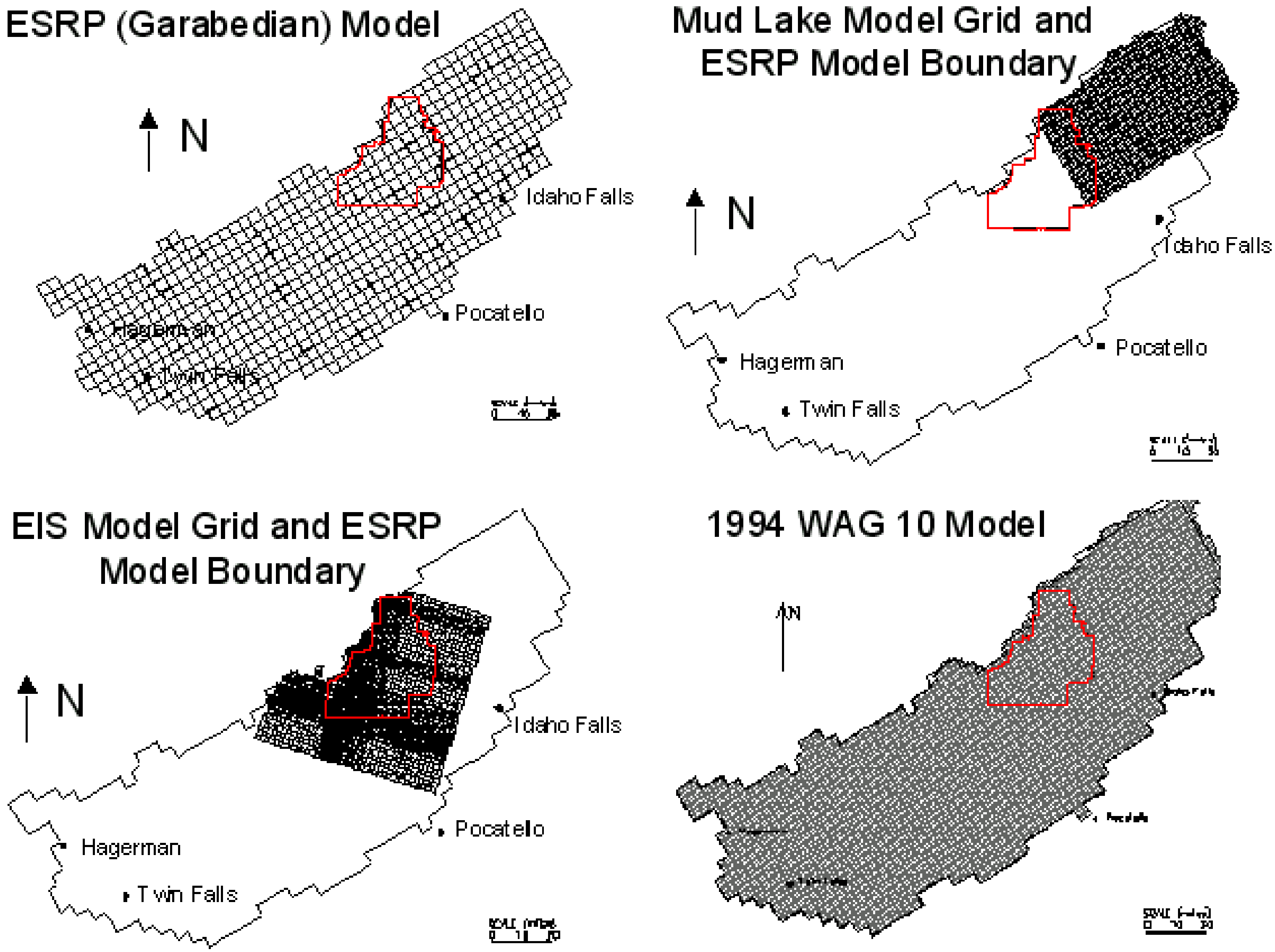


Figure 1-2. Domain and horizontal grids of four early regional and subregional models.

1.5.1.3 USGS ESRP Model (1992). A numerical flow model of groundwater underlying the entire ESRP was prepared as part of the USGS regional aquifer systems analysis (Garabedian 1992) for management of the groundwater supply. This model did not include contaminant transport. The four-layer model was prepared using MODFLOW. Vertical variations in head within each model layer were assumed to be negligible, and head losses between layers were assumed to be controlled by confining beds near the base of each layer. This layered modeling approach is referred to as a quasi-three-dimensional or multi-aquifer approach and is not fully three-dimensional. The model grid consisted of uniformly dimensioned cells that were 4 mi on a side (Figure 1-2). The model layers varied in thickness. Grid axes were also rotated for better alignment with the principal direction of regional groundwater flow.

The steady-state model was calibrated by the zonation approach using hydraulic conductivities and river conductances within reasonable ranges. Isotropic conditions were assumed for horizontal movement. The initial conditions for the transient model were derived from a pre-irrigation steady state, and the model simulated water level changes from 1891 to 1980 by adding recharge from irrigation. The model is most useful for summarizing regional data and providing estimates of regional properties. Although issues exist regarding several features of this model—including tributary valley average annual underflow rates and transmissivity values near the INEEL—the understanding of the overall regional flow system gained by development and application of the ESRP model provides helpful background information for the SWGM.

1.5.1.4 USGS Mud Lake Water Resource Model (1994). The USGS constructed a numerical groundwater flow model using MODFLOW to evaluate changing water-management practices in the Mud Lake area (Spinazola 1994). This model was a subregional, five-layer model consisting of a uniformly sized grid of 40 rows and 64 columns with each cell 1 mi on a side, aligned similar to the ESRP model (rotated approximately 31° counterclockwise). The model domain, representing 2,200 mi^2, is shown in Figure 1-2. Layers represented sub-unit thicknesses ranging from 100 ft at the top of the aquifer to almost 1,000 ft at its base.

Head-dependent flux boundary conditions were used for the southwest boundary and for a portion of the southeastern boundary. No-flow boundary conditions were used for parts of the northwestern boundary that abut mountain ranges and for parts of the southeastern boundary. Specified flux conditions were used for portions of the northwestern boundary corresponding to tributary underflow and also to simulate recharge from precipitation and withdrawals for pumping and irrigation.

The steady-state model was calibrated to 1980 conditions using the trial-and-error approach with multiple conductivity zones per layer. Some transient conditions were also calibrated. Evaluation criteria included configuration of measured and simulated water tables—in particular, the shape and position of specific contours. Significant discrepancies resulted between measured and simulated water levels. These discrepancies were from apparent cumulative effects of uncertainty in several components of recharge and discharge.

1.5.1.5 INEEL WAG 10 Regional Flow Model (1994). Prior to the current OU 10-08 modeling effort, several WAG 10 models were developed. These included models developed on both regional and subregional scales.

In 1994, a regional flow model was developed to support WAG 10 objectives using MODFLOW. These objectives included modeling future transport and defining regional flow at individual WAG scales. This model's domain covered the entire SRPA and was the same as the USGS ESRP model. Similar four-layer, quasi-three-dimensional approach and boundary conditions were used as well as similar recharge/discharge estimates. The USGS model discretization was subdivided from 4 mi per grid side to 1 mi per grid side to provide better resolution for individual WAG modeling. This is shown with the other models in Figure 1-2.

The 1994 WAG 10 model combined hydraulic conductivity zones from the USGS ESRP, Mud Lake, and EIS models. This allowed greater detail in the area immediately upgradient of the INEEL. The 1994 WAG 10 model successfully integrated INEEL and ESRP scales with regard to groundwater flow. Steady-state and transient conditions were used to calibrate hydraulic head, gradient, and overall water budget. The model was calibrated only to targets within the INEEL boundary and only within the top layer of the model. Hydraulic gradient targets were satisfied at intermediate scales but not local scales. The larger scale of the model limited the accuracy of the hydraulic gradient and flow directions for defining the regional setting of the local scale. The 1-mi grid size proved too coarse to define boundary conditions at individual WAG scales.

1.5.2 Current Modeling Efforts

The following subsections discuss several modeling efforts currently under way to define regional and subregional groundwater flow and transport in the SRPA and in the vicinity of the INEEL. The Idaho Water Resources Research Institute (IWRRI) at the University of Idaho is preparing a new water resources model. The USGS is developing new subregional flow and transport models. In addition, three WAG-specific groundwater models that have been developed are of interest to the OU 10-08 groundwater modeling team.

1.5.2.1 State of Idaho Regional Water Resource Model. The State of Idaho has developed groundwater models to support management of water resources and, in particular, adjudication of groundwater and surface water rights on the ESRP. Currently, the IWRRI's Eastern Snake River Plain Aquifer Model Enhancement Program is updating and refining a regional SRPA flow model (Wylie 2003). The purpose of the effort is to better detail the extent and thickness of the aquifer domain by using grid refinement in areas of intensive groundwater use and groundwater/surface water interaction, particularly along the eastern and southeastern margins of the ESRP, and to improve the understanding of water table dynamics over the past 20 years.

The model consists of a single layer (two-dimensional) with variable thickness. The model grid consists of 104 rows and 209 columns of uniformly sized cells, with cell dimensions of 1 mi on a side. Grid axes are aligned with the principal direction of regional flow (rotated 31.4° counterclockwise). The model domain is shown in Figure 1-3 relative to INEEL boundaries. In the IWRRI model, the aquifer is treated as a confined system. The central focus of the model is on the interaction of the groundwater flow system with the Snake River and on seasonally varying inputs from tributary valley underflow.

1.5.2.2 USGS Subregional Model. The USGS is currently developing a conceptual model that will support preparation of next-generation flow and transport models for a subregional domain surrounding the INEEL.[1] The features of the USGS conceptual model include multiple layers, variable aquifer thickness, and three major hydrogeologic units.

The current USGS conceptual model encompasses an area of 1,940 mi^2, including most of the INEEL, and extends 75 mi from northeast to southwest and 35 mi from northwest to southeast (Figure 1-3). The aquifer is treated as an equivalent porous media with nonuniform properties. Three hydrogeologic units are used to represent the hundreds of known individual basalt flows and sedimentary interbeds. These include younger rocks of fractured basalts and permeable sediments; younger rocks of

1. Ackerman, D. J., S. R. Anderson, L. C. Davis, B. R. Orr, G. W. Rattray, and J. P. Rousseau, 2001, *A Conceptual Model of Flow in the Snake River Plain Aquifer at and near the Idaho National Engineering and Environmental Laboratory with Implications for Contaminant Transport*, U.S. Geological Survey Draft Report.

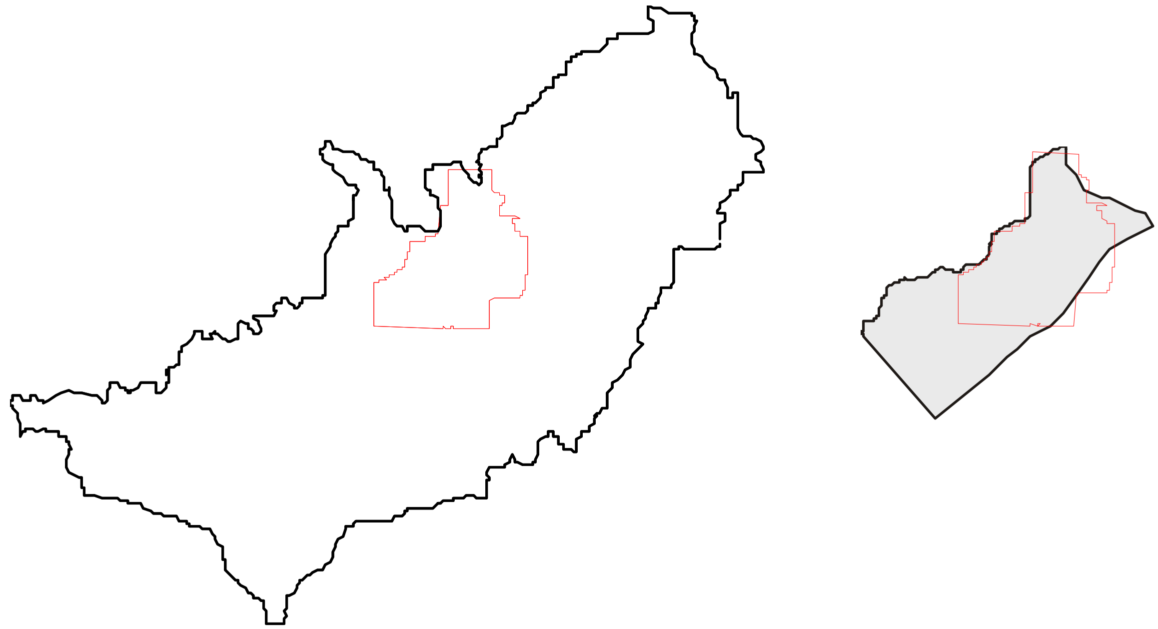


Figure 1-3. Model domain extent for two contemporary modeling efforts (IWRRI, left; USGS, right).

dense basalt and less-permeable sediments; and older rocks of much-less-permeable, altered basalts and interbedded sediments. The predominance of sedimentary interbeds in some areas of the INEEL might lead the USGS to incorporate in its conceptual model a fourth hydrogeologic unit that represents increased sediment percentage in these areas.

The conceptual model developed as part of the current USGS modeling study differs from conceptual model elements of the proposed SWGM. These differences include the estimates of maximum thickness of the effective aquifer, areal distribution of thickness, and downward flow and deep circulation of contaminants. The USGS model uses an assumed base of the aquifer as delineated primarily from electrical resistivity soundings. These soundings indicate that the aquifer base ranges from 700 to 4,800 ft below land surface. This results in an active aquifer thickness of over 3,500 ft in some areas of the domain. This maximum thickness is significantly larger than that of the current OU 10-08 conceptual model. Additionally, the distribution of aquifer thickness differs from thickness distributions now being developed by OU 10-08, although the USGS thickness distribution generally trends from thinner in the north to thickest just south of the INEEL boundary.

Boundary conditions include a no-flow boundary to the southeast that corresponds to a groundwater flow path, as determined from the Garabedian (1992) model. Constant-flux boundaries are used to the northeast and southwest. Specified-flux boundaries are used along the northwest boundary to represent tributary underflow. Some downward groundwater flow is being included in areas of known vertical gradient, especially where the less-permeable, massive basalts apparently intersect the water table south of the INEEL. This implication of downward flow and deeper circulation of contaminants that migrate offsite is a third conceptual model difference from the OU 10-08 conceptual model.

1.5.2.3 INEEL Individual WAG Models. Numerical groundwater flow and contaminant transport models are in use for WAGs 1, 3, and 7. The WAG 3 and 7 models were developed to be coupled with vadose zone models. The WAG 1 model was developed for CERCLA risk assessment of the aquifer without vadose zone modeling. These three models are based on different numerical solution codes, grid dimensions, and contaminants of concern summarized in Table 1-1.

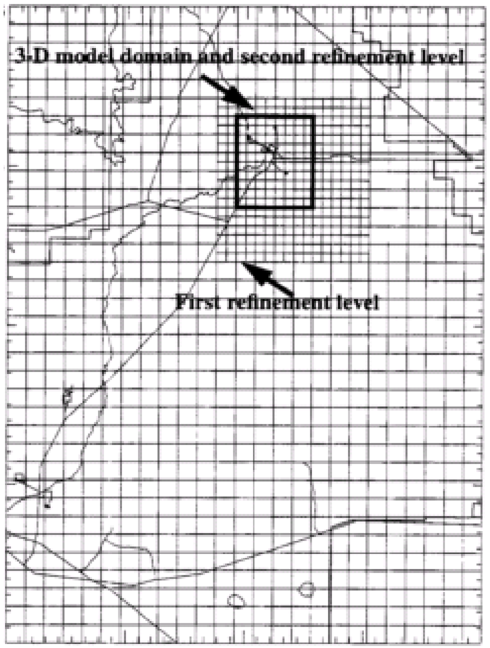
Table 1-1. Summary of numerical modeling activities for WAGs 1, 3, and 7.

Waste Area Group	Model Code	Grid Dimensions	Contaminants of Concern
WAG 1 (TAN)	TETRAD, converted to MODFLOW, no vadose zone model	5,249 ft (82 ft refined)	Trichloroethene
WAG 3 (INTEC)	TETRAD, coupled with a TETRAD vadose zone model	1,312 ft (656 ft refined)	Strontium-90, technetium-99
WAG 7 (RWMC)	TETRAD, coupled with a TETRAD vadose zone model	1,000 ft (500 ft refined)	Carbon tetrachloride

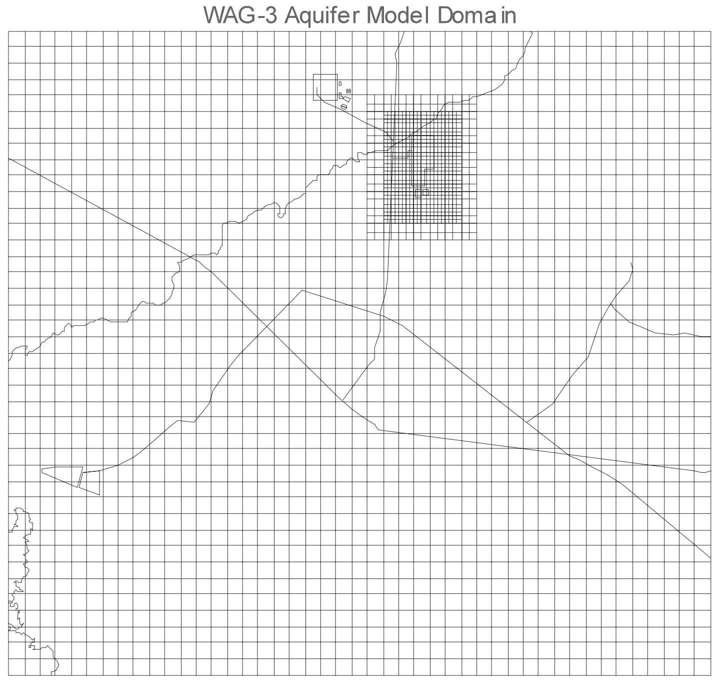
1.5.2.3.1 WAG 1—The WAG 1 model consists of a saturated-only domain with a point source representing direct injection of waste to the SRPA via the TAN injection well (i.e., Technical Support Facility [TSF]-05) and gradual release from a secondary source (i.e., sludges in the SRPA around the injection well). The model contained 5,249-ft base grid dimensions but was refined over six levels down to an 82-ft grid dimension within the source area (injection well). The model includes a far-field domain (i.e., the portion of the INEEL extending from TAN to the southern INEEL boundary). The model is a multi-layered, fully three-dimensional model dominated by the QR interbed. The model was initially developed using TETRAD but was later converted to MODFLOW using a smaller domain. An effective porosity of 0.03 was required to match tritium breakthrough observed in monitoring wells. The model is shown in plan view in Figure 1-4.

1.5.2.3.2 WAG 3—The WAG 3 saturated groundwater model was prepared using the TETRAD code and coupled with a TETRAD vadose zone model that simulates contaminants reaching the aquifer. The steady-state confined aquifer model consists of 18 layers, with vertical refinement at the HI interbed. Horizontal grid dimensions are 1,312 ft per side for the base area and 656 ft per grid side in the refined area. A plan view of the model is shown in Figure 1-4. The model includes flux from the Big Lost River and was calibrated using tritium data from the INTEC injection well.

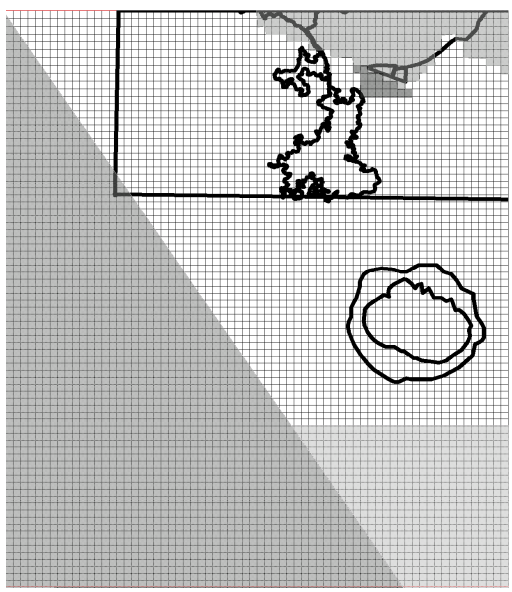
1.5.2.3.3 WAG 7—The saturated groundwater model developed for WAG 7 is coupled to the WAG 7 vadose zone model. Both models use the TETRAD numerical code. The saturated model consists of a three-dimensional, seven-layer system employing five constant conductivity media types. The horizontal grid dimensions are 1,000 ft per side, with grid refinement in the vicinity of the RWMC's Subsurface Disposal Area to 500 ft per grid side (Figure 1-4). The model domain was recently extended to the southwest and now extends several miles south of the INEEL boundary. After this modification, the domain extends 12.9 mi from east to west and 15.3 mi from north to south. The flow model was calibrated to water level data from the fall of 2003. Relative to the original domain, the fit between observed and simulated heads with the extended domain was poorer; this prompted discussion on the need for a new OU 10-08 sitewide groundwater model to support individual WAG models.



(a) WAG 1 groundwater model



(b) WAG 3 groundwater model



(c) WAG 7 groundwater model

Figure 1-4. Model domain and grid layout for three individual WAG models.

2. MAJOR ISSUES

The SRPA beneath the INEEL has been studied during the past 40 years by multiple institutions to solve a variety of problems. Several numerical groundwater-modeling programs have been developed by INEEL contractors, the USGS, and state agencies, as described in the preceding section. Because multiple organizations have long investigated this complicated, heterogeneous, anisotropic, fractured-rock aquifer, a number of issues will likely be encountered during development of the SWGM. In an effort to recognize and address problems in advance of model development, a list of challenges was compiled at a summit meeting held with the regulatory agencies in Idaho Falls, Idaho, on June 16, 2004. The identified challenges include the following:

- Influence of system uncertainties
- Integration of and consistency with other WAG models
- Identification of calibration targets and performance of multi-objective calibration
- Capability of the model to be adapted to accommodate advances in knowledge
- Communication of model information to the public, management, DOE, and regulatory agencies
- Identification, prioritization, and filling of data gaps
- Identification of receptors and risk scenarios
- Identification of criteria for success both in technical credibility and stakeholder acceptance of results.

The following subsections discuss how these issues will be addressed during development of the SWGM.

2.1 Influence of System Uncertainties

Uncertainty analysis for the flow and transport model will involve several steps, namely (a) identification of uncertainties related to model input parameters, (b) prioritization of these uncertainties with respect to the sensitivity of model output to these uncertainties, (c) sensitivity analysis to confirm the ranking of the prioritization of the uncertainties, and (d) communication of the uncertainties with respect to the results of the model output. In addition, the analysis of uncertainties will include an internal and external peer review process to ensure the adequacy of the overall process and will include a methodology for incorporating stakeholder input.

The following three areas of uncertainty have been recognized to date and will be addressed during model development:

- Conceptual model
- Parameters
- Estimates of contaminant mass loading from individual WAGs.

Additional areas of uncertainty will likely be identified in the future and will be addressed as they arise.

Multiple organizations working independently to solve specific objectives have generated conceptual models of SRPA flow and transport, and, predictably, these models are not always consistent with one another. The data density and/or state of the science do not allow complete resolution of all discrepancies, so the SWGM approach will have to incorporate variations in conceptual model uncertainty as an integral component. This issue will be addressed by allowing flexibility in the model-user interface so that changes in the conceptual model can be made to evaluate the influences of different interpretations of the subsurface on flow and transport. Differences in conceptual models that generate small variations will be used to define and bound uncertainty calculations. Where variations in output are large, it might be necessary to collect additional data to better define the conceptual model.

Parametric uncertainty is a problem common to all simulations of aquifer flow and transport and will be addressed in the SWGM. A simple approach would be to apply a reasonable range of uncertainties to parameter estimates and treat it in a Monte Carlo probabilistic approach.

The SWGM will rely explicitly on output from individual WAGs that undergo a full RI/FS for mass loading of contaminants to the aquifer. The reasons for this are (a) the individual WAGs have the expertise and experience to make the best estimates of source volumes and release rates, (b) this information characteristically is reviewed and negotiated with agency counterparts over a period of years, and (c) the individual WAG models of flow and transport are used in RODs, and, therefore, any changes to source terms and aquifer loading might affect legally binding agreements. For these reasons, the SWGM will directly employ contaminant output from individual WAGs and, where provided, use the uncertainty estimates for flux to the aquifer from these same models.

Although the SWGM will rely explicitly on output from individual WAGS, it is recognized that the contaminant loading to the aquifer is *the* key input affecting the predicted future groundwater concentrations. As such, the appropriateness of the individual WAG vadose zone models and the underlying assumptions included in their development will be reviewed as part of using the simulated fluxes from those models.

2.2 Integration and Consistency with Other WAG Models

A key objective of the SWGM is integration and consistency with other WAG models in terms of numerically smooth transition between models, consistency of parameters used in INEEL models, and completion of the OU 10-08 model to coincide with completion of individual RODs. The approach to achieve consistency is to incorporate technical experts from major WAGs as part of the OU 10-08 team, conduct regular meetings among technical staff to discuss the SWGM, and integrate facility-scale discretization into a regional numerical model.

2.3 Identification of Calibration Targets and Performance of Multi-objective Calibration

This work plan has identified the following potential calibration targets for the SWGM:

- Water levels
- Contaminant plumes
- Geochemistry
- Water temperature.

Calibration targets will be selected and evaluated during model development using the data quality objective process to resolve different opinions on flow controls and directions. In particular, the fast-flow pathway interpretation must be consistent with all data sets (contaminant chemistry). Also, the thermal signature needs to be evaluated to see whether it is sufficient and appropriate for use in model calibration.

2.4 Capability of the Model to Accommodate Changes

An essential criterion for the OU 10-08 numerical model will be that it is readily capable of accommodating changes in input parameters. Due to the limited data available, there will be significant uncertainties in interpretations (i.e., interpretations of data sets are non-unique). Therefore, it is critical that the model be flexible enough to adapt to changes created by new data or advances in understanding. The following are modifications that might have to be incorporated into the model:

- Incorporation of the "fast flow path" inferred from natural isotope analysis
- Testing of hypotheses, i.e., thickness of the aquifer
- Modifications of hydrostratigraphic units when new information (i.e., thickness, continuity, and layer top and bottom elevations) becomes available
- Modifications of the hydraulic property zone distribution
- Modification of the domain size
- Adjustments in boundary conditions, such as tributary drainage basin underflow.

The SWGM is a true three-dimensional model and, therefore, requires large input files. Making any modifications via adjustments in parameters within individual input files can be extremely difficult. Some modifications, such as varying the aquifer thickness, might require completely re-gridding the domain, reassigning aquifer properties, and changing boundary conditions. Accommodating such changes by simply adjusting parameters of input files is impossible. Use of a graphic interface is desirable in order to modify the model in a relatively easy and straightforward manner.

Recent OU 10-08 modeling has focused on the graphical user interface system known as the Groundwater Modeling System (GMS), which was developed by the U.S. Army Corps of Engineers for a consortium of federal agencies, including the DOE (BYU 2002). As such, contractors supporting DOE groundwater modeling have access to GMS. GMS is a comprehensive software package that provides tools for every phase of a groundwater simulation, including site characterization, model development, post-processing, calibration, and visualization. GMS is the only graphical user interface that supports triangulation-irregular networks, solids, borehole data, two- and three-dimensional geostatistics, and both finite-element and finite-difference models in two and three dimensions. GMS employs a conceptual model approach for building models using Geographical Information System objects and has excellent post-processing tools, including animation of transient results. The graphic interface greatly facilitates constructing and modifying the model.

The user interface of GMS allows easy conversions of conceptual models to numeric models, allows quick updates that result from conceptual model changes, prepares model input files, and processes output. The GMS graphical user interface allows the user to make changes to hydrological features in the conceptual model using a click-and-drag approach with the computer mouse. Model input files are updated automatically. GMS supports several finite-difference and finite-element groundwater flow and transport codes, such as MODFLOW, MT3DMS (an improvement over MT3D), and FEMWATER. All of the previously mentioned possible modifications of the SWGM can easily be made using GMS. Therefore, the planned OU 10-08 numerical model will be readily capable of accommodating changes in input parameters.

2.5 Information Transfer

The SWGM will help transfer information to the general public, management, DOE, and regulatory agencies. The numerical model will be capable of providing visual aids for presentations on INEEL remediation activities. Modeling efforts will include preparation of maps and other visual aids.

The SWGM will support the cumulative risk tool used for composite analyses. The model will be used to assess the cumulative risks associated with commingled contaminant plumes at the INEEL.

2.6 Identification and Prioritization of Data Gaps

The inherent flexibility of the SWGM will provide the capability to identify and assess significant data gaps. Modeling runs will be conducted to consider the reduction in uncertainty by the acquisition of new field or laboratory data. By estimating costs for filling data gaps, informed management decisions can be made about whether to fund new field or laboratory work. Some data needs cannot be optimized, or perhaps even anticipated, until the model is actually used in the evaluation process. When possible, and when resources allow, data gaps will be filled as modeling progresses.

2.7 Identification of Receptors and Risk Scenarios

The overall goal of the SWGM is to evaluate and ensure protection of human health and the environment for existing and potential downgradient receptors that use groundwater from the SRPA. A key component in achieving this goal will be defining the receptor locations and use scenarios in the risk assessment in a concurrence process with the stakeholders. The risk scenarios will be established through communication and meetings with representatives from the DOE, the Idaho Department of Environmental Quality, and the EPA. Because the goal is evaluating cumulative risk in groundwater from all WAGs, the SWGM will be consistent with the most current conceptual models for OU 7-13/14 and OU 3-14.

2.8 Identification of Criteria for Success

To assess the SWGM, a list of criteria for success will be negotiated with the regulatory agencies through regularly scheduled conference calls and special meetings, as appropriate. The development of criteria will help avoid the common pitfall encountered when models are considered failures because they do not perfectly represent every aspect of system behavior. Realistically, no single model can perfectly represent a complex, natural system. History shows that successful development of a model takes place in sequential steps, whereas necessary data qualification and additional site characterization efforts take place in parallel.

The SWGM is a practical effort designed to achieve a constrained set of objectives in increasingly complex steps. The effort will start with a two-dimensional model that has variable aquifer thickness designed to model groundwater flow at the INEEL site. This model will be quite flexible and allow for modeling smaller-scale local issues as well as large-scale problems. Domain boundaries, heterogeneities, point sources, sinks, and other factors can be introduced easily when using a GMS interface. Execution times for running the model will be relatively short; therefore, many runs can be made to test a large variety of hypotheses. The model can also be expanded to two or more layers, which might better describe the physical groundwater system at the site. As greater understanding is gained and data gaps are filled, increasing complexity can be added to the model.

Identifying the process as open-ended is important. Some data gaps that are important, if not critical, in clarifying the conceptual model and calibrating the numerical flow model have already been identified. Other data needs cannot be firmly ascertained until uncertainty analyses and preliminary simulations are completed. Therefore, the process of filling the gaps and assessing the criteria for success cannot be done “up front” but will extend over the life of the project. Resources will be needed over time to progressively and deliberately reduce uncertainty by optimizing acquisition of new data after incorporating the latest information.

With the preceding discussion in mind, the following “working” categories of data have been identified for use in the calibration process (Section 7 provides more details on the calibration process for the SWGM):

- Contaminant concentrations at given locations, which are used to assess impacts to groundwater quality at extraction points (e.g., water wells)

- Contaminant arrival distributions in time and space, which are used to assess human, ecological, economic, and social/cultural impacts from contaminant release

- Water table elevation at given locations and times, which is needed for situations when the elevation is not constant because of changes in recharge (e.g., this is useful for planning well placement, managing water resources, and siting future facilities)

- Groundwater flow rates and dispersion of contaminants, which are needed to quantify the initial dilution of contaminants from the vadose zone and injection wells so that contaminant-plume migration and fate can be modeled.

The SWGM has the potential to satisfy all of the above criteria, but as discussed in other parts of this work plan and is true of all contaminated sites, uncertainties in many parameters to be incorporated in the model raise concerns about the level of accuracy that can ultimately be achieved in the final risk predictions. Cumulative risk over long timeframes can only be evaluated using models, and models are inherently subject to short- and long-term uncertainties that limit the accuracy of predictions. There is no easy solution to this dilemma, except to recognize the limitations and strive to minimize their effects.

The SWGM presented here will “bound” the possible cumulative risk outcomes and will continuously and progressively reduce uncertainty. The success of the SWGM effort will ultimately be determined by reducing the uncertainty associated with the above criteria to a level acceptable by all affected parties.

3. INTEGRATION APPROACH

The OU 10-08 modeling team must address the numerous interdependencies with other major INEEL modeling activities. Consideration of these interdependencies is critical in order to ensure that the SWGM meets the regulatory-driven requirements for OU 10-08: assessing risk to the SRPA from the entire INEEL site, ensuring long-term protection of the SRPA via selected remedies, and maintaining institutional memory and modeling capabilities over the long term (decades) in the event that updating the models is needed to make CERCLA-related decisions.

Substantial effort will be expended on integration during the OU 10-08 RI/FS process, in particular, communication with personnel from other WAGs and modeling groups, regulatory agency involvement during work plan development, and external peer review to foster technical credibility. These activities will help to ensure that the end product is acceptable to all parties involved.

3.1 Integration with Existing and Planned Models

Perhaps the most important technical aspect of the SWGM will be its integration with contaminant transport models that have been developed for the individual WAGs—most importantly, WAGs 1, 3, and 7. As discussed in Subsection 2.2, the approach to integration with other WAG models will be to include senior technical experts from the individual WAGs in the OU 10-08 modeling team and hold regular technical meetings with the individual WAG teams to discuss SWGM development. These meetings will be held at least quarterly throughout the development period to exchange ideas. All significant documentation developed by the OU 10-08 modeling team (see Subsection 8.1) will be reviewed by the individual WAG teams through the Idaho Completion Project internal review process before transmittal to the regulatory agencies.

This SWGM effort is driven from the bottom up by modelers and geoscientists to ensure that the final product can be used with existing and planned models. The SWGM will support smaller-scale, WAG-specific groundwater models. Aspects of the SWGM such as boundary condition inputs, local-scale flow conditions, and grid spacing will interface directly with the smaller-scale WAG models, and, at some point, the SWGM will likely be used for aquifer (not vadose zone) flow and transport simulations to support the individual WAGs. This will facilitate the long-term ability to revise models once RODs are in place for individual WAGs.

Integration with groundwater models is not limited to INEEL-based models. The OU 10-08 modeling team is interfacing with modelers from the USGS and the State of Idaho to enhance consistency with other simulations of aquifer flow and transport. In addition, data being used by modelers from the USGS and the State of Idaho will be assessed to see if any of their data can add value to areas of sparse data in the SWGM. This extra effort will produce a model that is not only internally consistent but also, to the extent possible, consistent with models of the surrounding areas. Although the intent is to make the SWGM consistent with the models from other entities, consistency might not be possible in all situations. The SWGM will reflect the best data and judgment currently available and will not sacrifice potential accuracy purely for the sake of consistency. As a result, the SWGM will provide the INEEL with a powerful tool for summarizing aquifer conditions and communicating them to a wide range of audiences.

3.2 Two-dimensional Model Used to Design Three-dimensional Model

To enhance integration with the numerous parties involved in modeling aquifer flow and transport in the region, the project will use a tiered approach to the model design. Numerical simulations will start with a simple two-dimensional model to identify problems—such as flow field issues, localized versus regional issues of scale, and usability of certain well data—that we hope to resolve in the final fully three-dimensional SWGM. The two-dimensional model will also be the means for opening communication with interested stakeholders—such as personnel from other WAGs, the USGS, and state and federal agencies—on the scope and breadth of the SWGM. This approach should help to identify technical and administrative areas of conflict early enough in the process to solve issues before the SWGM is completed.

3.3 Agency Concurrence – Modeling Summit Meeting

On June 16, 2004, a modeling summit meeting was held in Idaho Falls, Idaho, with representatives from the DOE Idaho Operations Office, the Idaho Department of Environmental Quality, and the EPA. The purpose of the meeting was to present the current status of the SWGM, reach consensus on the groundwater modeling objectives, and compile a list of challenges to be considered during development of the SWGM. The objective statement and the list of issues to be addressed are presented in Subsection 1.1 and Section 2, respectively.

Agency summit meetings will be held as appropriate during model development to keep lines of communication open between technical staff and decision-makers. Likewise, status updates will be provided during monthly agency conference calls. As stated previously, regulatory agency review and approval will be required on all major documents and deliverables for this project.

3.4 Peer Review

To ensure the technical quality and enhance the credibility of the SWGM among stakeholders, an external peer review was held during development of this work plan. In addition, when significant activities are about 60% complete, an external peer review team will review them. An external peer review will also be used to evaluate the completed SWGM. This will help ensure that products developed by the OU 10-08 modeling team for the regulatory agencies are of high technical quality (see Subsection 8.1).

The external peer review was implemented during the development of this work plan, with an external team peer review of the modeling approach and objectives on May 19 and 20, 2004. The external review team consisted of Drs. Edgar Berkey (chair), R. L. Bassett, Michael Kavanaugh, and Peter Wierenga. These individuals are former members of the Groundwater/Vadose Zone Expert Panel at DOE's Hanford Site, where they worked for more than three years to resolve many of the same issues being faced by the OU 10-08 modeling team. In addition, members of the external peer review team are recognized as being generally knowledgeable about groundwater issues within the DOE complex.

The external peer review team fully endorsed the effort to develop and implement a comprehensive, sitewide, fate and transport model at the INEEL. Although members of the external peer review team recognize that the development task will be challenging, they believe that the task is doable with reasonable effort and investment. Moreover, the existence of a sitewide groundwater model will yield significant dividends by allowing more confident and defensible predictions of the cumulative impacts of INEEL operations on the underlying SRPA. Members of the external peer review team believe that this effort will be essential in promoting and securing stakeholder concurrence and in establishing new missions at the INEEL. The external peer review team provided a list of seven recommendations for the OU 10-08 modeling team. These recommendations were made available to all technical project members and the regulatory agencies, and a letter containing the recommendations is provided in Appendix A. The recommendations were taken into account during preparation of this work plan and will be addressed during model development.

Brief biographical sketches of the external peer review team members' relevant experience for this work are presented below.

Edgar Berkey: Dr. Berkey is a senior consultant to the DOE, the EPA, and industry. He is also a vice president of Concurrent Technologies Corporation and has over 35 years of experience in this field. He received a B.S. degree in chemical engineering from Stanford University and a Ph.D. degree in nuclear science and engineering from Cornell University. He was a member of DOE's Environmental Management Advisory Board for six years, EPA's Science Advisory Board for four years, and chairman of the Groundwater/Vadose Zone Expert Panel at Hanford for three years. He currently chairs the Energy and Environmental Technology Directorate Review Committee for the INEEL and is also a member of the Laboratory Advisory Committee and the Environmental Technology Directorate Review Committee at the Pacific Northwest National Laboratory. In addition, Dr. Berkey is a member and former chairman of the Environmental Advisory Committee for DOE's Savannah River Site. Dr. Berkey has been an adjunct associate professor of environmental engineering at the University of Pittsburgh and co-director of the EPA-funded Groundwater Remediation Technologies Analysis Center.

R. L. Bassett: Dr. Bassett is president of Geochemical Technologies Corporation. For 14 years, he was a professor in the Department of Hydrology and Water Resources at the University of Arizona, where he continues as an adjunct professor and directs the isotope laboratory. He holds a B.S. degree in geology from Baylor University, an M.S. degree in geochemistry from Texas Tech University, and a Ph.D. degree in environmental geochemistry from Stanford University. He has been a principal investigator for numerous field and laboratory research projects such as DOE siting studies in Arizona. He has published extensively in peer-reviewed journals on issues related to radioactive waste geochemistry, groundwater geochemistry, siting, isotopic geochemistry, and contaminant migration and transport. He was a Darcy Distinguished Lecturer and an associate editor for the journals of *Water Resources Research*, *Ground Water*, and *Applied Geochemistry*. He has served on numerous review committees, panels, and boards, such as the University of Waterloo Centre for Groundwater Research Advisory Committee; the National Academy of Sciences Committee on Low Level Radioactive Waste; the Argonne National Laboratory Radioactive Waste Review Panel; the Board of Directors of the National Ground Water Association; Association of Ground Water Scientists and Engineers; and the Hanford Ground Water/Vadose Zone Expert Panel.

Michael A. Kavanaugh: Dr. Kavanaugh is vice president and the national science and technology leader for Malcolm Pirnie, Inc. He has over 30 years of consulting experience as a chemical and environmental engineer to private- and public-sector clients in the United States, in Western Europe, and for the World Bank. His areas of expertise include hazardous waste management, soil and groundwater remediation, strategic environmental management, risk analysis, water quality (with an emphasis on emerging contaminants), water treatment, water reuse, industrial and municipal wastewater treatment, and technology evaluations, including patent reviews. He has served on many advisory panels at DOE facilities, including the Hanford Groundwater/Vadose Zone Expert Panel, and external reviews at the Oak Ridge National Laboratory, the INEEL, Lawrence Livermore National Laboratory, and Los Alamos National Laboratory. Dr. Kavanaugh chaired the Board on Radioactive Waste Management of the National Research Council from 1998 to 2000. He has B.S. and M.S. degrees in chemical engineering from Stanford University and the University of California (UC), Berkeley, respectively, and a Ph.D. in civil/environmental engineering from the UC Berkeley. He is a registered professional engineer in several states, is a diplomat of the American Academy of Environmental Engineers, is a consulting professor in the Environmental Engineering Department of Stanford University, and was elected to the National Academy of Engineering in 1998.

Peter J. Wierenga: Dr. Wierenga obtained an M.S. degree from Wageningen University in the Netherlands and a Ph.D. degree in soil physics from UC Davis. He taught soil physics for 20 years at New Mexico State University, where he had an active research program in water flow and contaminant transport through the vadose zone. With funding from the EPA, the Nuclear Regulatory Commission, the State of New Mexico, and others, he conducted many large field studies in cooperation with colleagues at New Mexico State University and the New Mexico Institute of Mining and Technology. Subsequently, he became a department head at the University of Arizona and led the transformation of a traditional soils department to a diversified environmental sciences department. For the past five years, Dr. Wierenga has been director of the Arizona Water Resources Research Center. At Arizona, he has performed field experiments on vadose zone processes with colleagues from the Hydrology Department and other departments. He was a member of the Hanford Ground Water/Vadose Zone Expert Panel and has published over 200 papers and reports, including over 100 as refereed journal articles. He is a fellow of the American Geophysical Union, the American Association for the Advancement of Science, and the Soil Science Society of America, and he is a highly cited author.

3.5 Agency Review and Concurrence

An objective of this work plan is to include an elevated degree of regulatory agency involvement in the development of the SWGM. Based on discussions held with the regulatory agencies at the June 16, 2004, modeling summit, an overall project statement of objectives was developed (see Subsection 1.1), and priority modeling issues were identified (see Section 2). The overall modeling objectives statement and issues resulting from the summit meeting are also documented in a letter from the DOE to the EPA and the State of Idaho dated July 28, 2004 (Shaw 2004).

In addition, rather than simply compiling a single final report of the SWGM results when the project is completed, a series of documents is planned for agency review and concurrence throughout the SWGM development. These documents will include a white paper on well site selection; a white paper on numerical code selection; a summary report on the subregional-scale, preliminary two-dimensional aquifer model; a report on the subregional-scale, three-dimensional aquifer model; and a report on the three-dimensional flow and transport model. These reports are described in Subsection 8.1. This plan is intended to significantly expand the agencies' involvement in the development of the model by engaging them early and frequently over the course of the project.

4. SYSTEM DESCRIPTION

The OU 10-08 numerical model will be developed to represent subregional groundwater flow and contaminant transport in the SRPA. The utility of this numerical model will depend, in large part, on how adequately it represents the SRPA and the geologic materials and processes involved with it. This representation is derived from the conceptual model. Subsequent subsections summarize key elements of the conceptual model, including the geologic setting, geohydrology, and geochemistry.

4.1 Geologic Setting

This subsection describes the geologic setting of the OU 10-08 model domain, including regional geologic and tectonic features, the geologic framework of the INEEL, and stratigraphic and lithologic features of the basalts and sediments of the SRPA. Features at the subcontinent scale are described first followed by features at the regional, subregional, and local scales.

4.1.1 Regional Geologic and Tectonic Features

The ESRP has formed within the context of very large-scale geologic and tectonic features (Figure 4-1). Several of these large-scale physiographic features that are pertinent to the formation of the ESRP are described below, including continental extension and concurrent Basin and Range faulting and the passage of the Yellowstone hot spot.

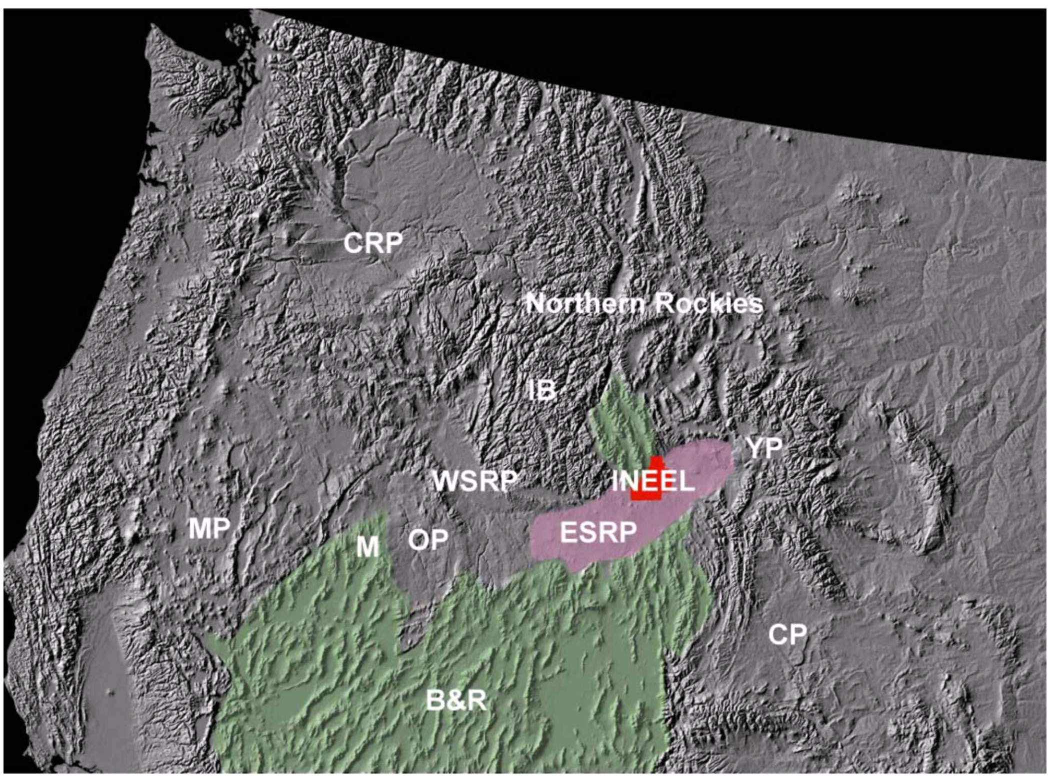


Figure 4-1. Large-scale physiographic features of the ESRP and environs. Labels denote the following features and locations: B&R - Basin and Range; CP - Colorado Plateau; CRP - Columbia River Plateau; ESRP - Eastern Snake River Plain; IB - Idaho Batholith; INEEL - Idaho National Engineering and Environmental Laboratory; M - McDermitt Caldera complex; MP - Modoc Plateau; OP - Owyhee Plateau; WSRP - Western Snake River Plain; YP - Yellowstone Plateau.

4.1.1.1 Continental Extension and Basin and Range Faulting. Faulting is an ongoing crustal response in the Great Basin, the ESRP, and the northern Basin and Range province to extensional deformation of the western United States. The orientation of extension in the region of the ESRP is northeast-southwest, and the southeastern Idaho area extends at a rate of about 1 in./year (Rodgers et al. 1990). The northern Basin and Range province accommodates the extension by normal faulting (also known as block faulting), producing north- to northwest-trending mountain ranges.

The Lost River and Lemhi ranges (Figure 4-2) are classic examples of the block faulting process. These ranges are over 60 mi long, 12 to 19 mi wide, and separated from each other by long, narrow basins that are about 12 mi wide. Each of the ranges is bounded on its southwest side by a normal fault, along which episodic faulting allows the basin to subside and the mountain range to move upward in response to the persistent extension of the region. The Lost River and the Lemhi faults are the closest major faults to the INEEL (Figure 4-2).

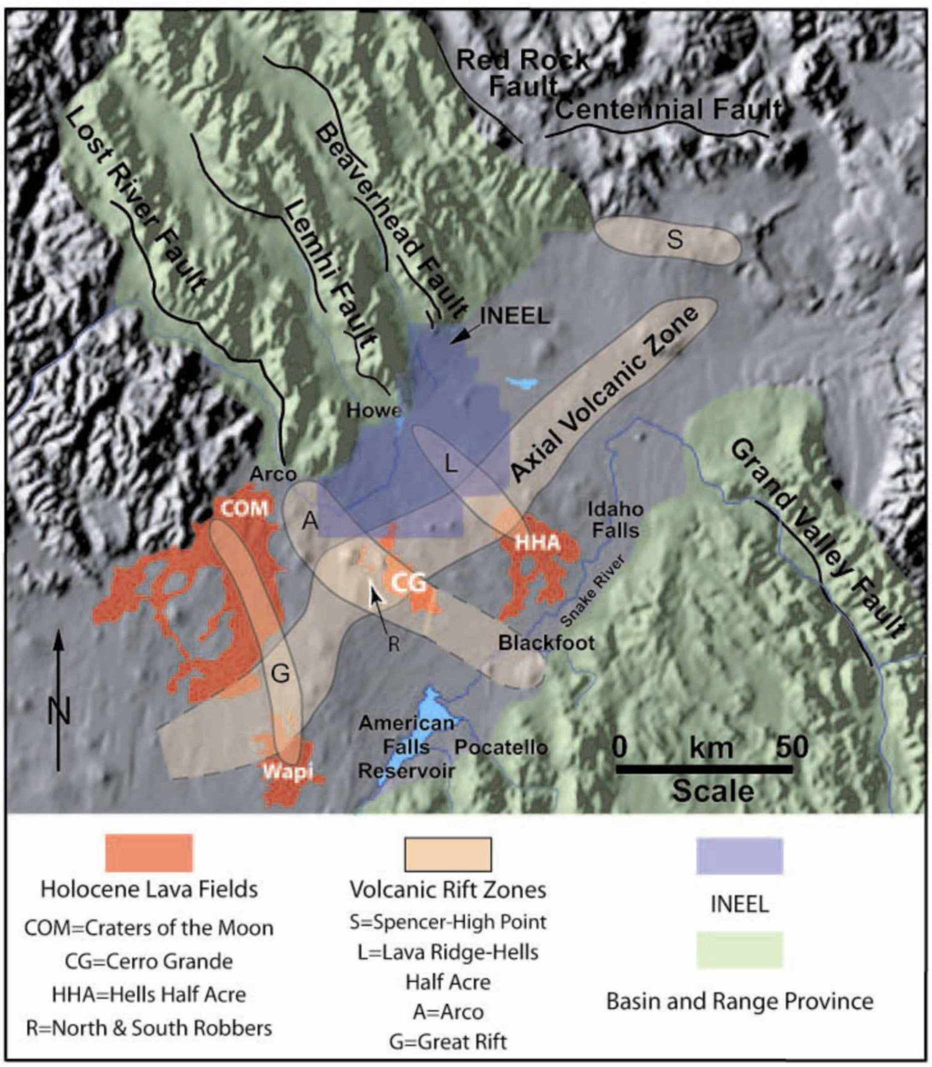


Figure 4-2. Map of the ESRP and environs, showing the location of volcanic rift zones, young lava flows, and major Quaternary faults.

The ESRP is an extensional feature, but unlike most of the world's extensional basins, no known boundary faults parallel the long axis of the plain, suggesting that the ESRP is not the down-faulted block of a graben subsequently covered with volcanic rocks. The exact nature of the ESRP subsidence with respect to the bordering Basin and Range mountains has been a subject of much discussion in the scientific literature. Whether boundary faults exist in the subsurface is an unresolved question. In the mountains bordering the plain, the axes of folds in Paleozoic sediments become progressively steeper toward the plain (Rodgers et al. 2002). This steepening might be evidence that the rocks of the Basin and Range flex downward and dive under the surficial volcanic deposits of the ESRP without faulting. The absence of evidence for boundary faults, however, is not evidence of absence, and the issue remains unresolved.

4.1.1.2 Yellowstone Hot Spot Track. The Yellowstone hot spot is commonly postulated to be a rising plume of hot mantle material beneath the North American Plate (Pierce and Morgan 1992; cf. Humphreys et al. 2000). As the southwest-traveling North American Plate passed over the hot spot beginning approximately 16 million years ago, the crust was heated and uplifted, and voluminous volcanism characteristic of that seen at Yellowstone National Park today created a sequence of rhyolitic calderas, ash flows, and tuffs. The thickness of these rhyolitic sequences is as much as several miles where encountered in outcrops on the Ohwyhee Plateau and at Yellowstone National Park and also in a 10,000-ft-deep drill hole at the INEEL (Pierce and Morgan 1992; Hackett and Smith 1992). The time-progressive line of calderas stretches from the ~15-million- to ~16-million-year-old McDermitt Caldera complex (see Figure 4-1) in northeast Nevada to the currently quiescent caldera at Yellowstone National Park. Figure 4-3 shows the rest of the hot spot track across the Owyhee Plateau and ESRP and ending at Yellowstone.

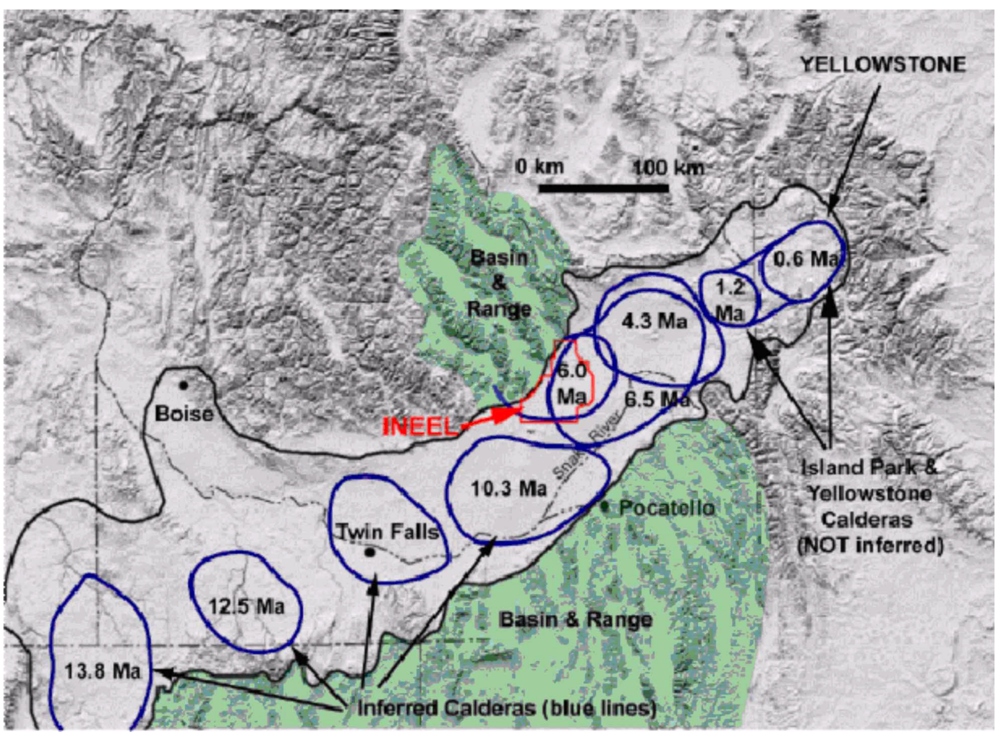


Figure 4-3. The Snake River Plain and Yellowstone hot spot track. The figure shows the northeastward trend of rhyolitic calderas and age progression from the 13.8-million-year-old Brundeau-Jarbridge volcanic field to the youngest caldera at Yellowstone National Park. The oldest portion of the hot spot track, the McDermitt Caldera complex (see Figure 4-1), is off the lower left corner of the figure. The four inferred calderas were located by mapping their remains exposed in outcrops along the edge of the Snake River Plain. The solid back line shows the areas subject to subsequent basaltic volcanism in the wake of the hot spot track. Shaded green areas are within the Basin and Range province (modified from Pierce and Morgan [1992]).

4.1.2 Eastern Snake River Plain

The ESRP, the dominant geomorphic feature of southern Idaho, is a northeast-trending zone of topographically subdued, late-Tertiary and Quaternary volcanic rocks that transects the northwest-trending, normal-faulted mountain ranges of the surrounding Basin and Range province (Pierce and Morgan 1992; Smith and Braile 1994) (Figure 4-2). The ESRP is bounded by the elevated volcanic highlands of the Owyhee Plateau at its southwest terminus and the Yellowstone Plateau at its northeast terminus. At the scale of the ESRP, geologic processes that have controlled the formation of the SRPA include subsidence, faulting and rifting, and basaltic volcanism.

4.1.2.1 Subsidence. It is currently thought that the interaction of the Yellowstone hot spot with the continental crust is responsible for the unique character of the ESRP. Passage of the continent southwestward over the stationary hot spot caused subsidence and widespread volcanism, thus creating the elongate volcanic province seen today. Total subsidence through isostacy of about 1 to 1.2 mi was caused by the increased load of dense, magmatic rocks emplaced in the middle crust and also by contraction of crustal rocks during cooling (Rodgers et al. 2002). Today, the subsiding basin extends from the Twin Falls, Idaho, area to the area southwest of the elevated Yellowstone Plateau, a distance of about 185 mi (see Figure 4-3). The continuing subsidence, coupled with the deposition of basalt lava flows and sediments, produced the low-relief and low-elevation character of the modern surface of the ESRP.

The area extending from Twin Falls to the Yellowstone Plateau is characterized by some of the highest continental heat flow in the world (Blackwell et al. 1991; Southern Methodist University 2004). Beneath the ESRP, this high-heat-flow area is masked beneath the cold water of the SRPA (Gass 1982). Thermal anomalies observed in both wells and hot springs occur along the margins of the ESRP where this high geothermal flux can escape the cooling effects of the aquifer. Anomalously high heat flow is also observed in deep wells that penetrate through the colder aquifer.

4.1.2.2 Basaltic Volcanism. The subsiding ESRP was covered with Pleistocene to Holocene basalt lava flows that were erupted from numerous volcanic vents throughout the ESRP. These basalts were intercalated with thin beds of sediments deposited by water and wind. This sequence of basalt flows and sedimentary interbeds covers the older rhyolitic volcanic rocks to depths of >0.6 mi, as can be seen in several deep drill holes in the INEEL area, in outcrops at Yellowstone, and in the Snake River Canyon (see Figures 4-2 and 4-3). The ESRP basalt province comprises the largest area of recent volcanism in the contiguous United States (Champion et al. 2002).

Basaltic volcanism continues on the ESRP, most recently occurring about 2,000 years ago along the Great Rift 19 mi south of the INEEL. Since passage of the Yellowstone hot spot, residual heat in the upper mantle continues to cause local melting. The exact nature and mechanism of this melting is an area of ongoing research (e.g., Hughes et al. 2002). Regardless of the actual source or cause, batches of basaltic magma occasionally accumulate in sufficiently large volumes to allow upward movement in thin dike-like conduits to the surface. Several researchers (e.g., Kuntz et al. 1992) postulate that magma tends to rise in preferred areas, producing northwest-trending volcanic rift zones, such as the Great Rift and the Arco volcanic rift zones (Kuntz et al. 1992; Hackett and Smith 1992) (Figure 4-2). Also, several eruptions tend to be clustered in time, with long periods of quiescence between eruptive clusters. For instance, in the Great Rift volcanic rift zone, eight eruptions have occurred within the past 15,000 years, but the lavas onto which the eruptions were deposited are several hundred thousand years old (Kuntz et al. 1992).

An "axial volcanic high" (AVH) extends northeast along the long axis of the ESRP (Figure 4-2). The AVH consists of a thick section of basalt flows that are topographically high (Figures 4-4 and 4-5) and divide the rivers and streams of the Basin and Range valleys to the northwest from those to the southeast. The Basin and Range rivers and streams immediately to the south are tributaries of the

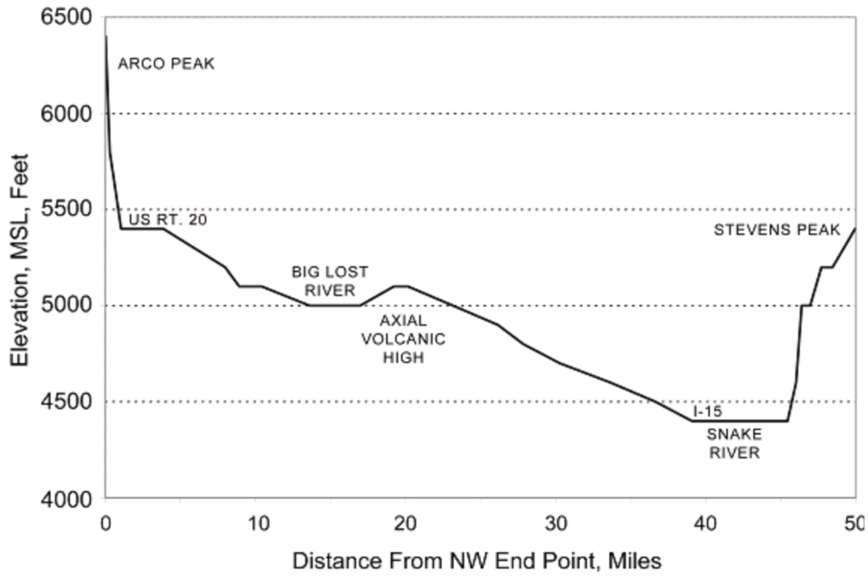


Figure 4-4. Elevation profile across the ESRP. This figure shows the elevation profile along a northwest-to-southeast transect from Arco to Blackfoot, Idaho. Note the subdued rise in elevation in the center of the ESRP due to the AVH.

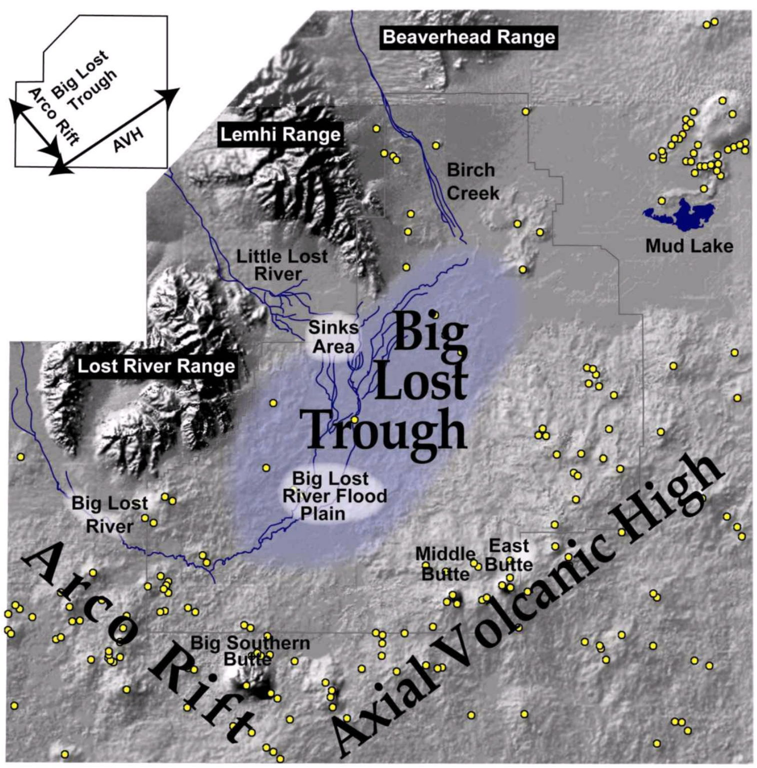


Figure 4-5. Physiographic features of the Big Lost Trough and the INEEL. Yellow circles are the locations of shield volcano vents and eruptive fissures. Dark blue lines and shapes are surface waters or river channels.

Snake River, whose waters eventually reach the Pacific Ocean. The Basin and Range rivers and streams to the north of the AVH, however, are prevented by the topographically elevated AVH from crossing the ESRP and reaching the Snake River.

4.1.2.3 Faulting and Rifting. Throughout the history of the ESRP, the area now composing the plain has experienced tectonic extension parallel with the Basin and Range regions to the north and south. The magnitude of this extension has been approximately 120% in a northeast-southwest direction. This extension has been partially accommodated by intrusion of magma in the form of dikes whose surface expressions are volcanic vents and fissures (Kuntz et al. 1992; Rodgers et al. 2002). Because the dikes respond to the same extensional stress field as the normal faults outside the ESRP, they are oriented to the northwest. The intrusion of northwest-trending dikes in the ESRP volcanic rift zones accommodates the extension of the plain and allows it to keep pace with the surrounding Basin and Range extension without normal faulting and large earthquakes (Parsons and Thompson 1991; Parsons et al. 1998).

The trends of fissure sets and lines of volcanic vents are parallel to subparallel with the plunging Basin and Range faults, all trending approximately northwest-southeast, perpendicular to the long axis of the ESRP and the AVH. Several of the major rift zones are exactly in line with Basin and Range faults north of the plain (Figure 4-2). These zones include the Arco Rift, aligned with the Lost River Fault, and the Lava Ridge-Hell's Half Acre Rift, aligned with the Lemhi Fault. At the northeast terminus of the ESRP, the Spencer-High Point Rift is aligned with the Middle Creek Butte Fault. Other rift zones, including the Great Rift, are not apparently aligned with pre-existing faults. Most ESRP researchers who work at the local and regional scales agree that a rift zone starts near Howe and Lava Ridge, extending to the fissures and vent of the ~5,200-year-old Hell's Half Acre flow. The number and location of other identified rifts are variable, e.g., Hackett et al. (1987) versus Anderson et al. (1999).

4.1.3 INEEL Area Geology

The geology of the INEEL is characterized by physiographic features that exert definite control on the flow of groundwater and migration of contaminants. The following subsections discuss these features and focus on volcanism at the subregional/INEEL scale.

4.1.3.1 Physiography. At the scale of the INEEL and OU 10-08, the important landforms are the Arco Rift, the AVH, the floodplain of the Big Lost River, and the sinks of the Big Lost and Little Lost rivers (Figure 4-5). A low-relief area, covered with a veneer of sediments and including the Big Lost River floodplain and sinks, is known as the Big Lost Trough (BLT). This feature is surrounded by higher-elevation features: the AVH to the south and southeast, the shield volcanoes of the Arco Rift to the southwest, and the Big Lost, Lemhi, and Beaverhead ranges to the west and northwest. To the north and northeast, the ESRP gradually rises in elevation. The shape and length of the BLT are dominated by the length of the Big Lost River on the ESRP.

The pattern of drainage and deposition in the BLT exists because of the AVH. The Big Lost River, the Little Lost River, and Birch Creek would flow to the Snake River to the east if not for the topographic high of the AVH. Instead, these streams historically have drained internally, terminating in playas and sinks on and near the INEEL. Dating the BLT stream, lake, and playa sediments in the subsurface establishes a minimum date for the BLT subsidence and the uplift of the AVH. Bestland et al. (2002), Blair (2002), and Blair and Link (2000) have argued that the BLT and AVH date from at least ~1.77 million years ago, based on a Big Lost River origin for Olduvai normal-polarity subchron lacustrine interbeds deeper than 985 ft in two deep INEEL coreholes, wells 2-2A and NPR-WO-2 (the minimum date of the Olduvai subchron is 1.77 million years ago).

4.1.3.2 Volcanism. The surficial basalts of the INEEL range in age from 16,400 years to 1.4 million years (Kuntz et al. 1992). Their combined thickness ranges from 0 to >0.6 mi. In general, ages tend to be youngest in the extreme south of the INEEL site (Figure 4-6), where the Holocene Cerro Grande Lava Flow crosses the INEEL border, and tend to be oldest north of TAN, where basalt age dates exceed one million years. The exceptions to this trend are the relatively small exposures of rhyolites that are 294,000 to 1.4 million years old in the Big Southern, East, and Middle buttes (Kuntz et al. 1994).

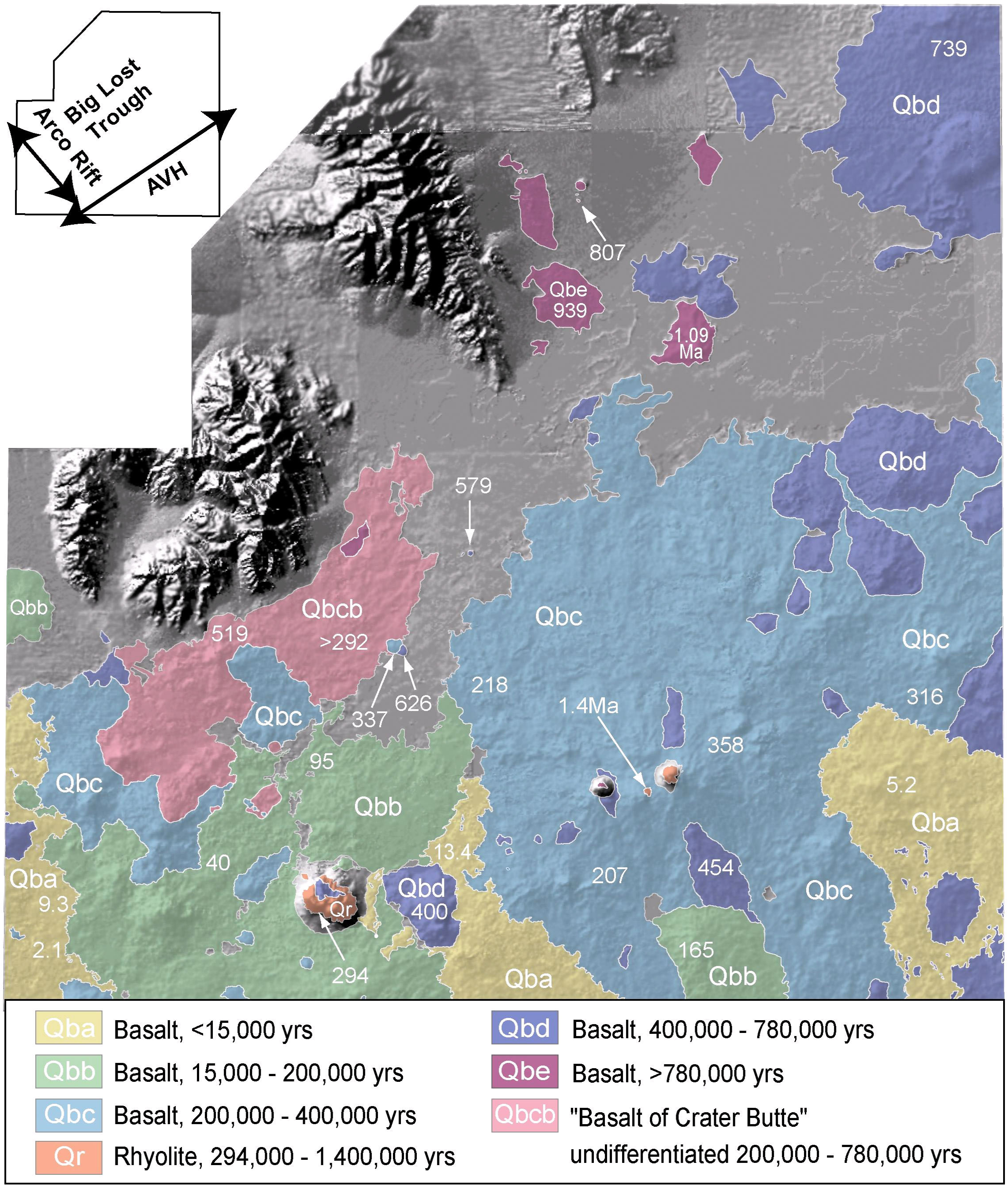


Figure 4-6. Surficial volcanic geology of the INEEL. Volcanic unit labels are explained in the map legend. This figure shows many of the age dates determined for the lava flows of the BLT, reported in ka ("kilo-anno") units.

Relatively recent Holocene volcanism has occurred at the southern end of the Arco volcanic rift zone just outside the southeast corner of the INEEL. The Cerro Grande, North Robbers, and South Robbers flows near Big Southern Butte are a little over 10,000 years old, and the Hell's Half-Acre lava field is about 5,200 years old (Figure 4-2). In contrast to the time-progressive northeastward migration of older silicic volcanism related to passage of the Yellowstone hot spot, there are no apparent patterns of spatial migration of basaltic volcanic centers with time on the ESRP. Basaltic volcanism on the ESRP is characterized by low-volume, effusive eruptions in which lava flows were emplaced through the low-angle shield volcanoes typical of the ESRP, from eruptive fissures, or from lava tubes (Greeley 1982).

Source vents for most of the basalt flows on the INEEL have been located in three general areas, as noted on Figure 4-5. These areas are near the boundary of the ESRP and the mountain ranges to the northeast along the AVH and along the Arco Rift, where the AVH and the Arco Rift come together. In general, it appears that the direction of flow for most basalts in the BLT has been away from these topographically high areas and toward the Big Lost River (Kuntz et al. 1994).

The position of the topographically low Big Lost River channel appears to have constrained the direction of flow for these basalts, controlling their distribution on the ESRP for much of the recent eruptive history at the INEEL. For example, basalt flows of Qbcb and Qbc basalt originating near the 519,000-year age date shown on Figure 4-6 in the southwest corner of the INEEL site first flowed southeast and east downhill toward the Big Lost River. After reaching the floodplain, some of the Qbcb basalts then turned east and northeast to flow in a direction sub-parallel to the river, based on flow directions mapped by Kuntz et al. (1992, 1994, 2003). Based on these same studies, lavas of various ages from the Arco Rift and nearby vents appear to have flowed in a north and northeast direction away from the topographically elevated buttes of the Arco Rift and AVH and toward the lower-elevation floodplain of the Big Lost River. Likewise, Qbc lavas originating near the East and Middle buttes (Figure 4-5) have been mapped as flowing northwest, away from the elevated AVH, and downhill toward the river. Figure 4-5 shows the locations of mapped volcanic vents exposed at the surface at the INEEL and environs; Figure 4-6 shows the distribution of basalt units and representative age dates; Figure 4-7 shows simplified flow directions for INEEL basalts, based on the mapping of Kuntz et al. (1992, 1994, 2003).

4.2 Hydrogeology

Numerous researchers have investigated various aspects of groundwater flow within the part of the SRPA that encompasses the INEEL. Arnett and Smith (2001) compiled many of these aspects into a conceptual model of aquifer flow. The OU 10-08 conceptual model is an extension of this compilation, integrating results from previous INEEL, USGS, and other geohydrologic studies. Work continues to refine the understanding of the geohydrologic framework and other components of the conceptual model. The following subsections describe the current understanding of the geohydrologic framework, the inflows and outflows, and the resulting groundwater field of flow.

4.2.1 Geohydrologic Framework

The part of the SRPA that lies within the OU 10-08 model domain consists of a complex section of layered basalt flows and sedimentary interbeds. The geohydrologic framework is defined as the distribution and thickness of the basalts and sediments, the hydraulic character of these basalts and sediments (hydrostratigraphic units), and the distribution of hydraulic properties of these hydrostratigraphic units.

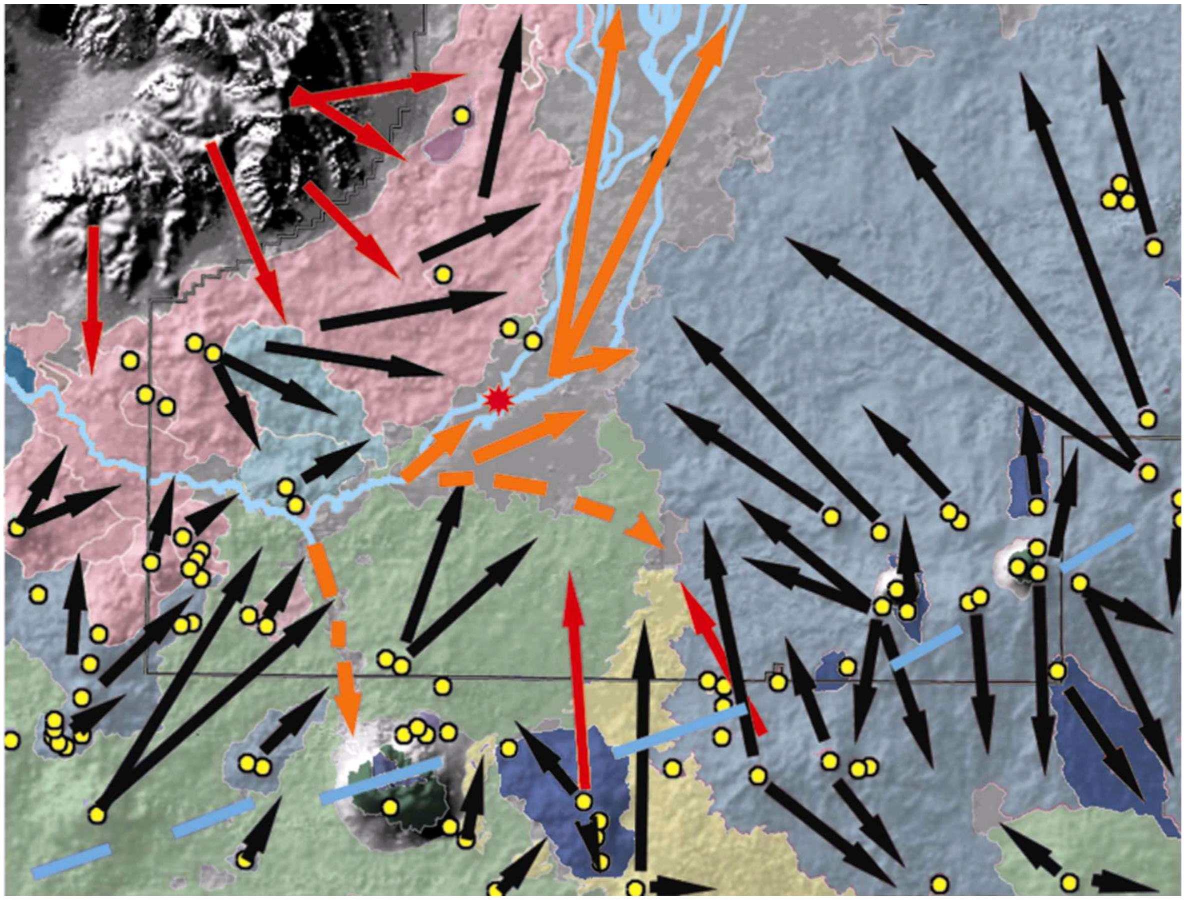


Figure 4-7. Directions of travel for lava flows and directions from source to deposition area for sediments for the Big Lost River floodplain. The black arrows show lava flow directions simplified from Kuntz et al. (1992, 1994, 2003). Red arrows show the estimated steepest gradient paths from upland alluvial sources. Orange arrows show the travel paths of river-transported sediments. Dashed orange arrows denote possible paleo-directions of sediment transport by the Big Lost River inferred from trends of mapped Quaternary playa deposits south and east of the current floodplain (Kuntz et al. 1994) and from mapping fluvial sands and gravel bars logged in the subsurface (Helm-Clark et al. 2004). Sediment deposition into the mostly flat sink areas of the Big Lost River, the Little Lost River, and Birch Creek in the northern half of the INEEL site is not shown in this figure (see Figures 4-5 and 4-8).

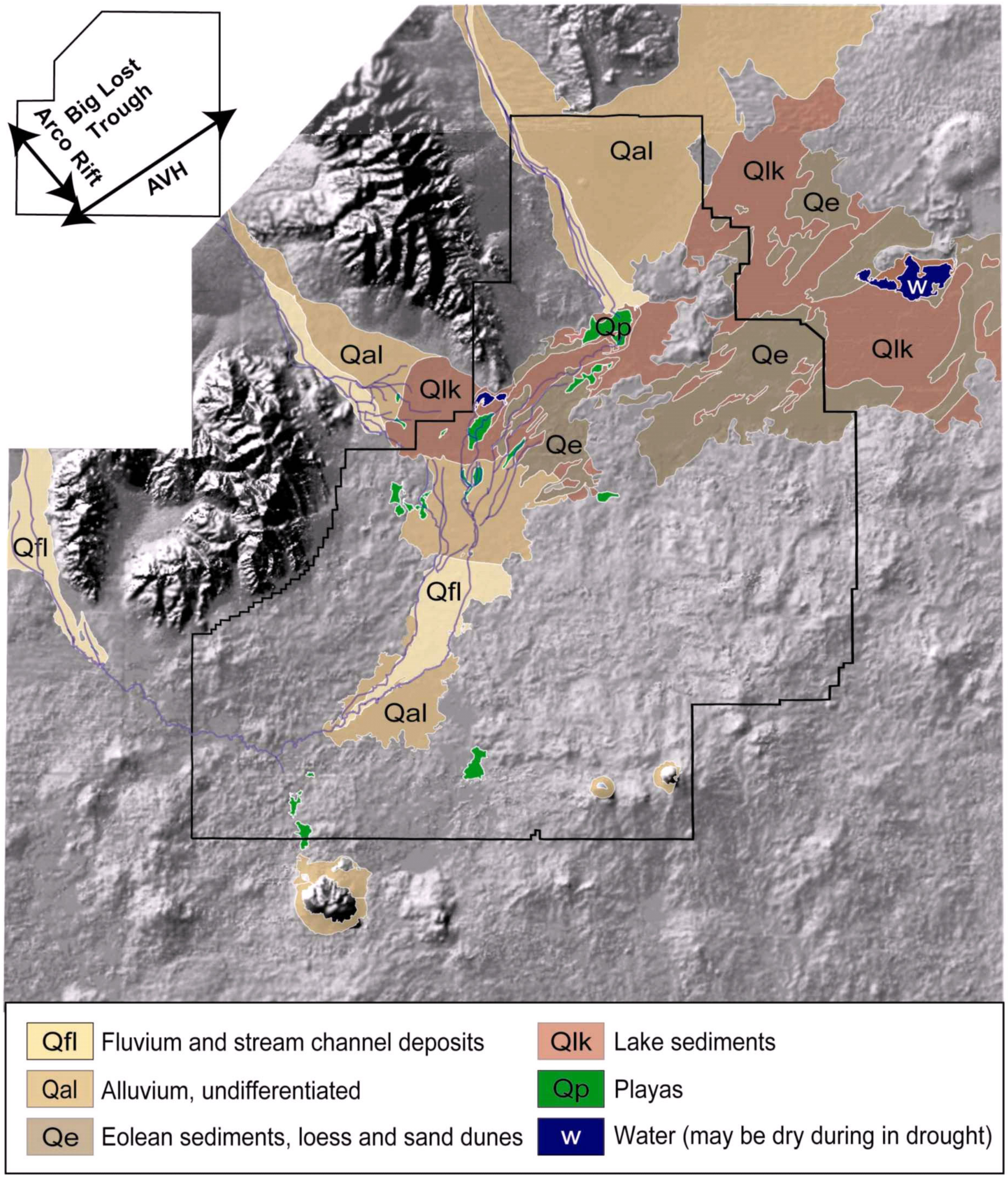


Figure 4-8. Distribution of surficial sediments of the INEEL and BLT areas. Sedimentary unit labels are explained in the map legend.

4.2.1.1 Aquifer Distribution and Thickness. The OU 10-08 model domain encompasses approximately 3,000 mi^2 of the ESRP. This entire area is underlain by the SRPA (Figure 4-9). The OU 10-08 model domain extends beyond INEEL boundaries to "better accommodate regional effects and to ensure that groundwater movement beyond the INEEL boundaries can be included" (Arnett and Smith 2001). The area is bounded on the northwest by the mountains and tributary valleys of the Bitterroot, Lemhi, Lost River, and Pioneer ranges. The southwest boundary corresponds to an

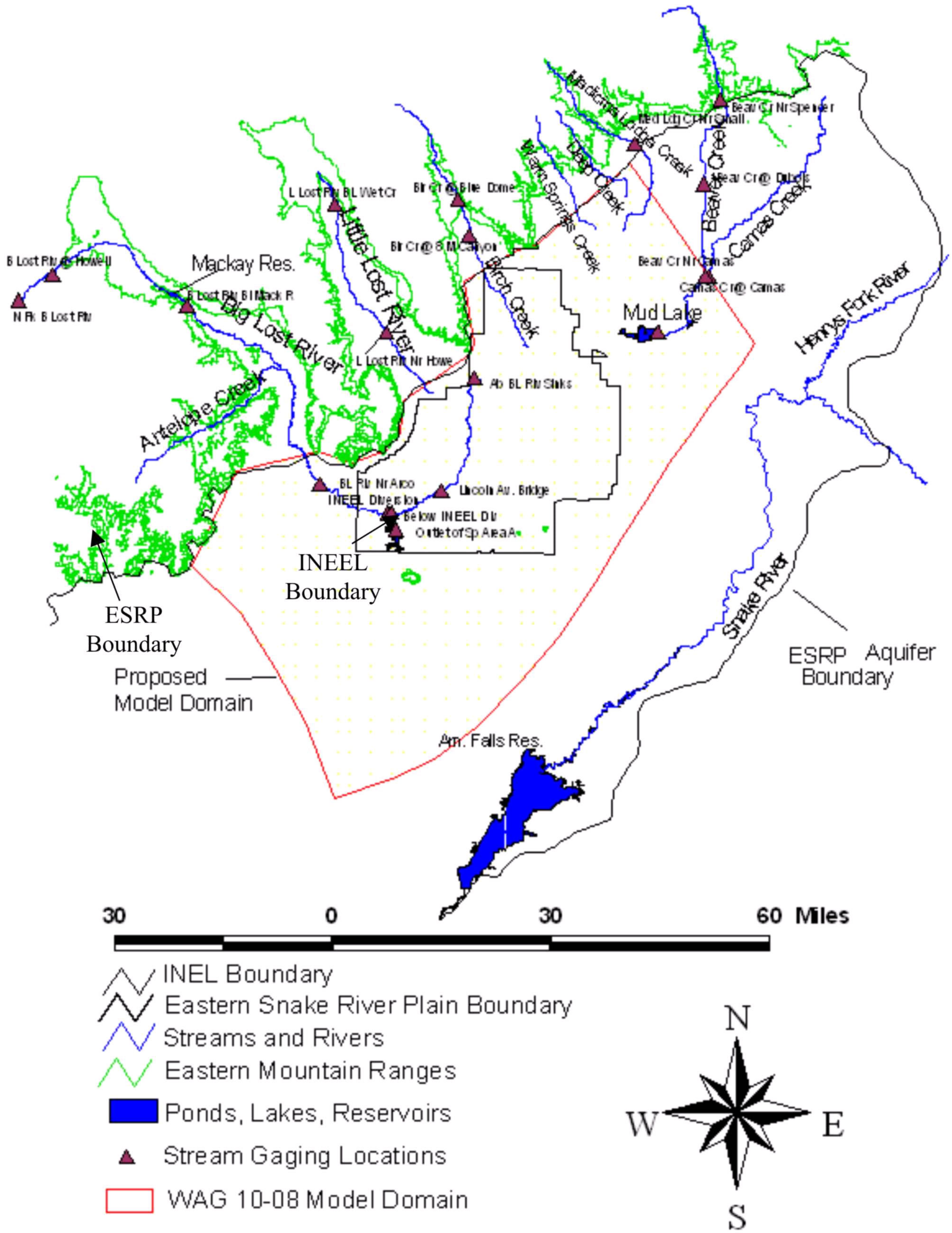


Figure 4-9. Location of the area of the ESRP represented by the OU 10-08 model domain.

equipotential line of the water table that is sufficiently downgradient from the INEEL to accommodate known and predicted contaminant migration over the next 10,000 years. The northeast boundary overlaps a part of the Mud Lake area numerically modeled by Spinazola (1994); this overlap permits the use of groundwater fluxes estimated in the Spinazola study to be used as underflow to the model domain. The southeastern boundary corresponds to a groundwater flow path defined by regional numerical modeling studies (Garabedian 1992; Ackerman 1995), across which no flow is considered to occur.

The thickness of basalts beneath the ESRP has been estimated primarily from electrical-resistivity geophysical data, because most SRPA wells penetrate only the upper part of the aquifer. Whitehead (1992, Plate 3) constructed a Quaternary basalt thickness map. Based on this work, the estimated basalt thickness in the area represented by the OU 10-08 model domain ranged from 100 to more than 4,000 ft. Lindholm (1996, p. A51) estimated that most regional groundwater flow in these basalts effectively occurs within the upper 500 ft of saturation.

Robertson (1974) estimated in a subregional solute transport study that the total aquifer system in the vicinity of the INEEL is probably more than 1,000 ft thick, but he used a uniform thickness of 250 ft in his numerical model to represent the upper active section of the aquifer, where most groundwater flow occurs. In subsequent years, this 250-ft thickness has been widely accepted as a good estimate of the active thickness of the SRPA. The active thickness of the SRPA is defined as the thickness through which most groundwater flow occurs.

More recent USGS subregional studies have based aquifer thickness largely on electrical-resistivity data. Aquifer thickness estimates from the current USGS conceptual model incorporate an upper unit consisting of younger, more transmissive, thin basalts; a middle unit consisting of thicker, less transmissive basalts; and a lower unit consisting of older, altered, and minimally transmissive basalts.[1] The estimated cumulative aquifer thickness used in the USGS model ranges from 0 to more than 4,000 ft in the vicinity of the INEEL.

The capacity of underlying units to transmit water is typically considered to be orders of magnitude smaller than that of the active aquifer thickness. Smith (2002) estimated the active thickness of the SRPA in the vicinity of the INEEL based on direct and indirect information obtained from wells and surface geophysical surveys. Most of the wells within the OU 10-08 model domain are constructed wholly within the upper part of the aquifer and provide no direct information about the active thickness. Direct information is available from only eight wells, located in the south-central part of the model domain, that fully penetrate the aquifer (INEL-1, Corehole 1, Corehole 2A, Site 14, C1A, WO-2, ANL-1, and Middle 1823).

Direct evidence of the active aquifer thickness in these wells was obtained through analysis of temperature gradients, lithologic variations in drill cores, and aquifer tests (Smith 2002). Elsewhere, aquifer thickness has been inferred from indirect measurements that include surface electrical-resistivity surveys and water-temperature data from wells.

A series of temperature studies has been conducted since the 1960s to examine heat flow and structural features (Blackwell 1989 and 1990; Blackwell and Steele 1992; Blackwell et al. 1992; Olmsted 1962; Smith et al. 2001; Brott et al. 1981; Wood and Bennecke 1994). Temperature logs from these studies provided direct information about the active thickness of the aquifer in the fully penetrating wells. The active thickness of the aquifer is characterized in these wells by nearly isothermal conditions, because the relatively fast-moving cold water in the aquifer dominates the regional geothermal gradient. Below the base of the active aquifer, the temperature profile represents the regional conductive temperature gradient (Figure 4-10). The active thickness of the aquifer in the eight wells ranges from 334 to 1,207 ft (Smith et al. 2001). Despite the sharp resolution of aquifer profile obtained from any given

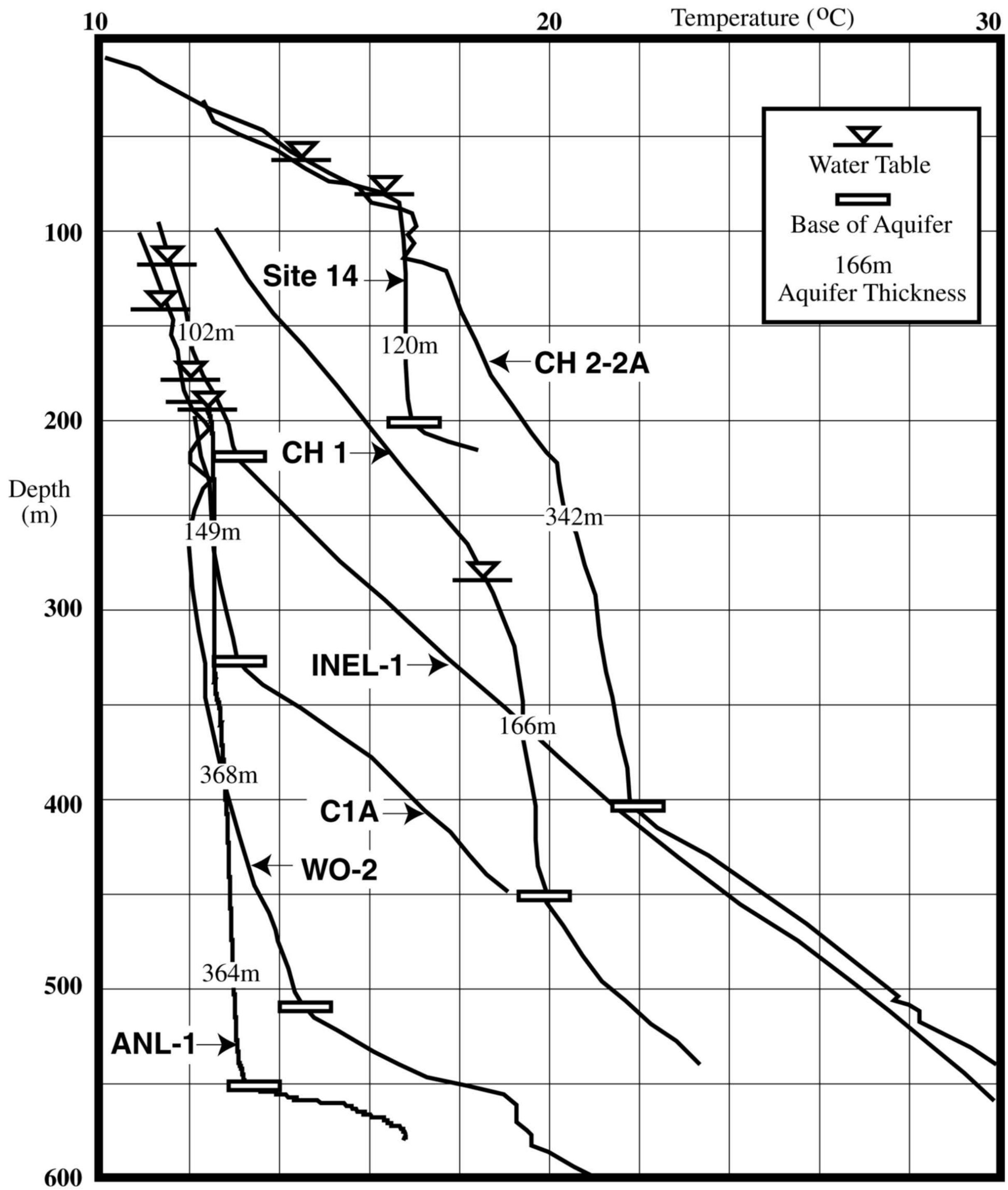


Figure 4-10. Temperature profiles in selected deep coreholes at the INEEL.

well, the lack of deep wells across the OU 10-08 model domain significantly limits the capability to establish an aquifer thickness profile across much of the INEEL site.

Cores collected from the deep wells provided additional information about the base of the active aquifer. In several wells, basalts characteristically were altered and mineralized below the depth of the temperature inflection that identifies the base. For example, Doherty et al. (1979, p. 3) observed propylitic alteration and secondary zeolite mineralization of the basalts below a depth of 1,600 ft in well INEL-1.

Additionally, aquifer tests conducted in several of the deep wells indicated that the hydraulic conductivity of rocks underlying the base of the aquifer is much smaller than that of the upper part of the aquifer. Mann (1986, p. 21) observed that the hydraulic conductivity of the upper section in the INEL-1 deep corehole (above a depth of 800 ft) is from two to five orders of magnitude larger than that of the section below a depth of 1,500 ft. Hydraulic conductivity in the upper section ranges from 1 to 100 ft/day; hydraulic conductivity of basalts below a depth of 1,500 ft ranges from 0.002 to 0.03 ft/day. Mann (1986, p. 18) also noted a distinct change in solute chemistry between the same depth intervals.

Two bounding estimates of thickness ("thick" and "thin") were developed for the OU 10-08 model domain (Smith 2002). Both used the limited direct evidence of the aquifer base from the eight deep wells in the south-central part of the model domain. The "thick" aquifer interpretation also utilized electrical resistivity data and water temperature at the top of the aquifer to extrapolate thickness estimates to the northeast and southwest. Colder water temperatures in those areas were correlated with assumed thicker aquifer sections, resulting in an upper bounding estimate for thickness distribution (Figure 4-11). The "thin" interpretation simply assumed a general tendency for aquifer thickness to become gradually greater toward the center of the plain and did not utilize water-temperature information away from the area of direct evidence (Figure 4-12). The thick aquifer and thin aquifer alternative interpretations are equally likely, and both will be considered in the OU 10-08 groundwater model.

4.2.1.2 Hydrostratigraphic Units. Hydrostratigraphic units incorporate rocks of similar hydraulic properties that function within the groundwater flow system as a single unit. The hydrostratigraphic units that contain the SRPA are derived from the particular nature of volcanism on the ESRP that includes plains-style volcanism (Knutson et al. 1990) and large-scale distribution of Quaternary and Tertiary basalts and sediments, a sequence of volcanic rift zones, and silicic volcanic features.

4.2.1.2.1 Basalts—The current understanding of the basalt stratigraphy of the SRPA within the area represented by the OU 10-08 model domain is based largely on subregional correlations by Anderson and Liszewski (1997). These correlations were made using geophysical logs and other data collected from wells and boreholes throughout OU 10-08. In some parts of the area, wells and boreholes are widely spaced and correlations are not well understood.

The SRPA within the OU 10-08 model domain consists of a complex section of numerous basalt flow groups and sedimentary interbeds. Anderson and Liszewski (1997) identified at least 178 distinct basalt flow groups, 103 sedimentary interbeds, six andesite flow groups, and four rhyolite domes within the vadose zone and aquifer at the INEEL.

The SRPA within the OU 10-08 model domain is generally composed of thin tube-fed pahoehoe flows (typically less than 30 ft thick) with numerous, very permeable, rubbly interflow zones and other basalt flow features (Figure 4-13) (Anderson et al. 1999). These basalt flows occupy the medial and distal parts of lava fields. In places, these basalt flows were ponded and are characterized by increased thickness, fewer interflow zones, and decreased bulk permeability. Near-vent flows are typically thicker than 30 ft but are characterized by high permeability. Basalts underlying this complex sequence are altered and mineralized, with much lower bulk permeability.

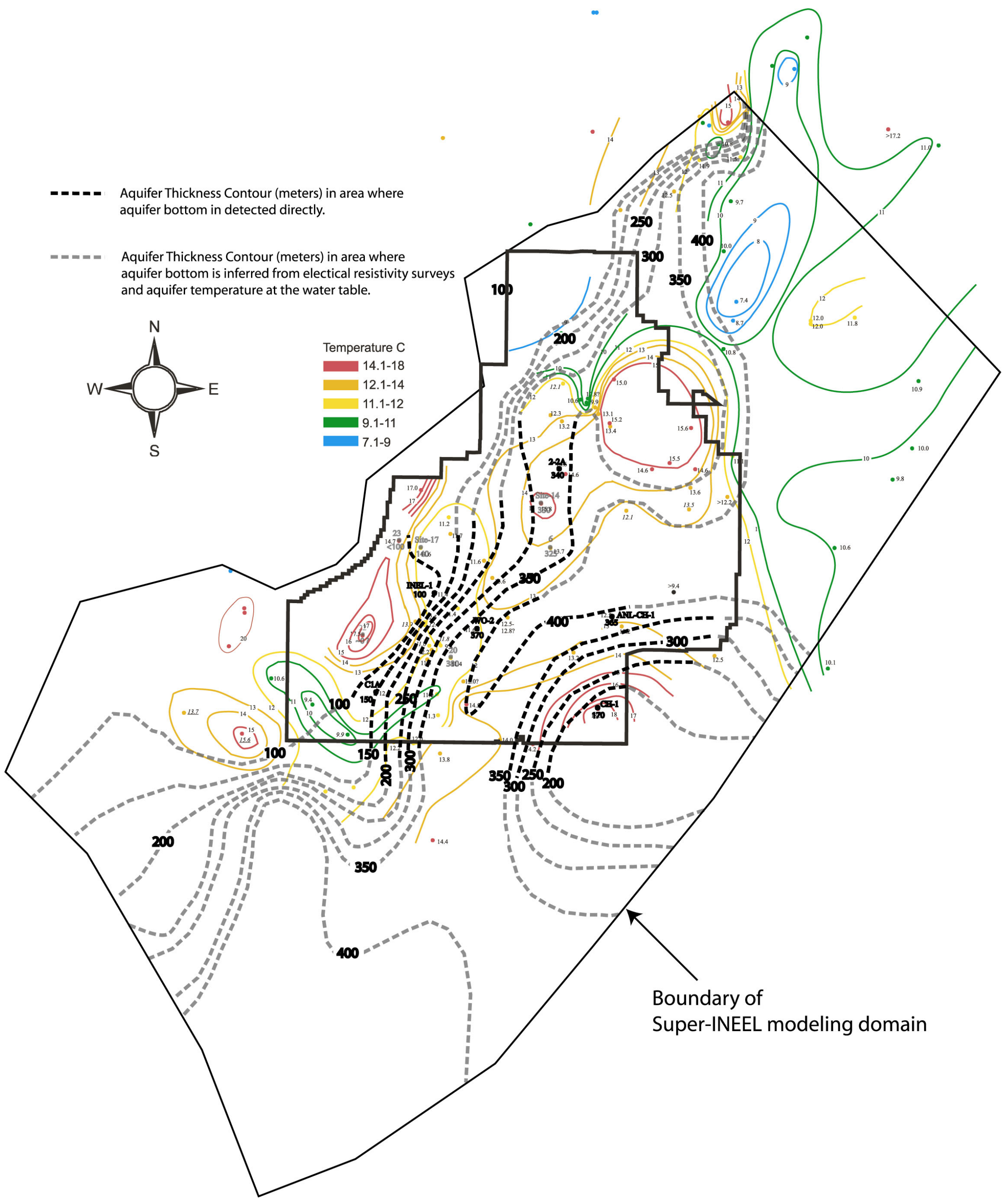


Figure 4-11. Smith's (2002) "thick" aquifer thickness distribution and SRPA water temperature in the area represented by the OU 10-08 model domain.

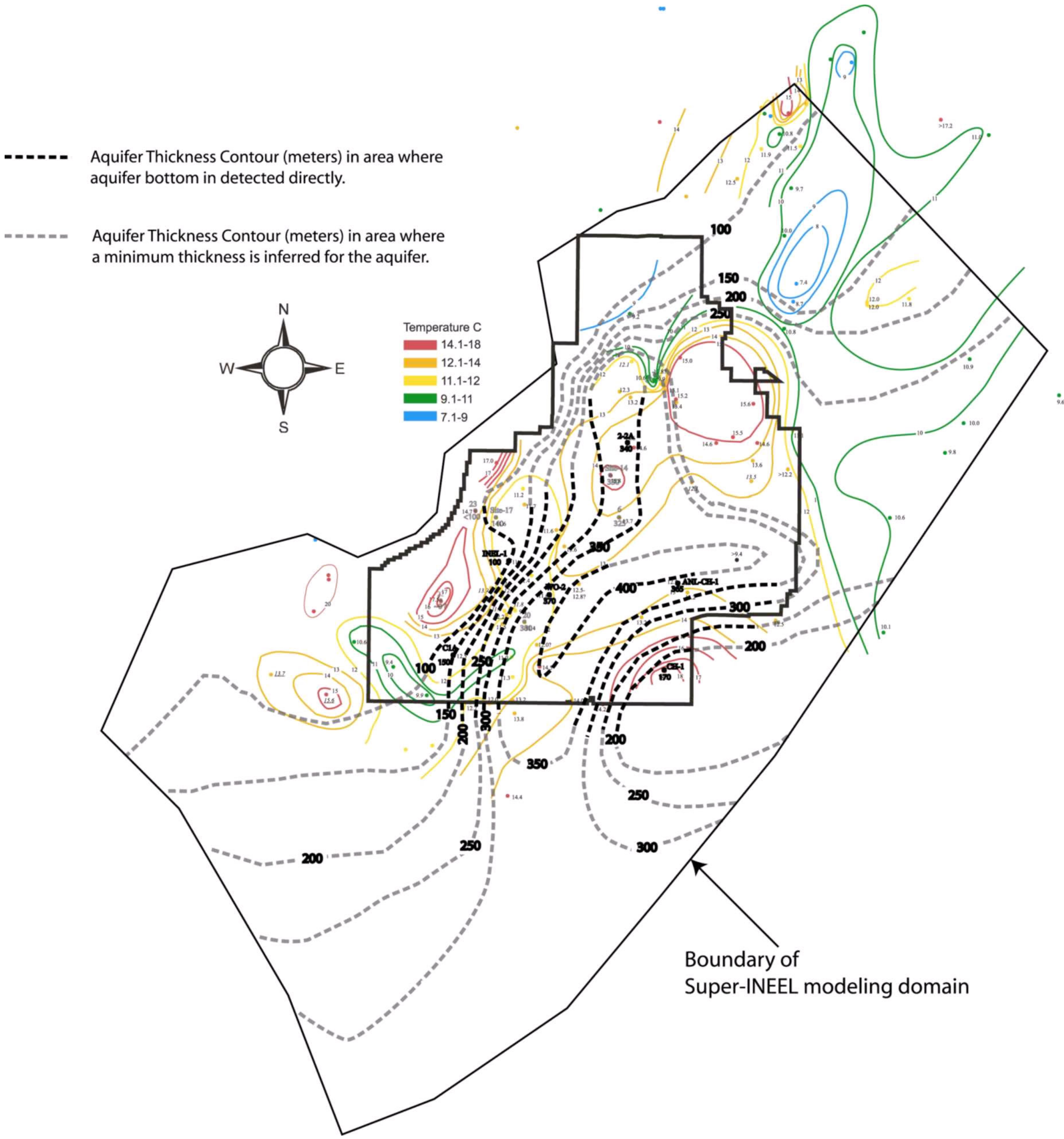


Figure 4-12. Smith's (2002) "thin" aquifer thickness distribution and SRPA water temperature in the area represented by the OU 10-08 model domain.